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Fueled Graphite Development (FTP/A 01330)

IRRADIATION PERFORMANCE OF HTGR FUEL
IN HFIR EXPERIMENT HRB-13

T. N. Tiegs

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ABSTRACT

Irradiation capsule HRB-13 tested High-Temperature Gas-Cooled Reactor (HTGR) fuel under accelerated conditions in the High Flux Isotope Reactor (HFIR) at ORNL. Irradiation space was shared by ORNL and the Los Alamos Scientific National Laboratory (LASNL); however, this report is concerned with only the ORNL part of the experiment. The ORNL part of the capsule was designed to provide definitive results on how variously misshapen kernels affect the irradiation performance of weak-acid-resin (WAR)-derived fissile fuel particles.

Two batches of WAR fissile fuel particles were Triso-coated and shape-separated into four different fractions according to their deviation from sphericity, which ranged from 9.6 to 29.7%.

The fissile particles were irradiated for 7721 h. Heavy-metal burnups ranged from 80 to 82.5% FIMA (fraction of initial heavy-metal atoms). Fast neutron fluences (>0.18 MeV) ranged from 4.9×10^{25} neutrons/m² to 8.5×10^{25} neutrons/m².

Postirradiation examination showed that the two batches of fissile particles contained chlorine, presumably introduced during deposition of the SiC coating. This resulted in chemical attack of the SiC coating by heavy metals and fission products and subsequent release of volatile fission products such as ¹³⁷Cs. The attack was apparently strictly temperature dependent. Although some correlation of particle failure fraction with deviation from sphericity was evident, the results are inconclusive because of the SiC corrosion. Even the "best" particles in the experiment showed unacceptable failure fractions.

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1. INTRODUCTION

Irradiation capsule HRB-13 tested High-Temperature Gas-Cooled Reactor (HTGR) fuel under accelerated conditions in the High Flux Isotope Reactor (HFIR) Removable Beryllium (HRB) facility at ORNL. The capsule was designed to provide both input for the HTGR recycle fuel product specification and irradiation space for advanced fuels for very high temperature reactors (VHTRs). The fuel product specification specimens were provided

by ORNL, and the advanced fuel specimens were provided by Los Alamos Scientific National Laboratory (LANL). This report is concerned with only the ORNL objectives in the experiment.

The ORNL portion of the capsule was designed to provide definitive results on how variously misshapen kernels affect the irradiation performance of weak-acid-resin (WAR)-derived fissile fuel particles.¹ Specific objectives of the experiment are

1. to determine the extent to which small satellites attached to the fuel kernels derived from the Rohm and Haas Amberlite IRC-72 resin affect irradiation performance,
2. to determine the extent to which numerous satellites attached to fuel kernels derived from the IRC-72 resin affect irradiation performance,
3. to obtain irradiation performance data on irregularly shaped fuel kernels or clusters of small fuel particles derived from the IRC-72 resin,
4. to evaluate the importance of slight eccentricity of fuel kernels derived from the Diamond Shamrock Company Duolite C-464 resin on irradiation performance,
5. to evaluate the importance of gross eccentricity of fuel kernels derived from the C-464 resin on irradiation performance, and
6. to test the effect of very irregular shapes on the irradiation performance of the C-464 resin.

The planned loading process for resin-derived kernels required that the first step be screening and shape-separating the as-received resin to a suitable size fraction before loading. The reject level of the as-received resin is about 80%. However, on a production basis it would be very difficult to remove all the nonspherical particles so that, after loading with uranium and drying, some irregularly shaped and nonspherical particles would be present. In the WAR fuel irradiated in previous capsules, the loaded resins were further upgraded to remove essentially all the irregularly shaped or nonspherical particles before carbonization and conversion. Thus, only "perfect" particles were irradiated, and no record was available for the performance of particles not meeting the kernel specifications. The HTGR Fuel Product Specification, at the time TRB-13 was designed, required that "no more than 10% of the kernels have a ratio of maximum diameter/minimum diameter >1.2 ." These specifications

were based on experience obtained with sol-gel and dense UC_2 kernels. The HRB-13 irradiation capsule was designed to address this problem directly and to study the extent to which the irregularly shaped kernels affect irradiation performance.

At the time HRB-13 was designed and fabricated, the reference recycle fuel was the WAR made with high-enriched uranium (HEU). However, at the present time the reference cycle for the HTGR uses fuel <20% enriched or medium-enriched uranium (MEU). This necessitates that the kernels be of high density so that enough heavy metal can be put into the core. Consequently, the inherently low-density WAR particles are no longer considered for use in an HTGR. Although the relevancy of the information has been diminished, this report documents the results obtained.

2. DESCRIPTION OF CAPSULE

The HRB-13 was similar in design to HRB capsules previously irradiated.²⁻⁴ The basic capsule design (Fig. 1) contained 40 fuel rod specimens in a graphite sleeve encapsulated in a dual-wall, stainless steel containment vessel.

The capsule was instrumented with eight Chromel vs Alumel thermocouples (C/A) located in the graphite sleeve (Fig. 1). Temperatures in the capsule were controlled and fission gas release was monitored by sweeping inert gases (helium and neon) through the capsule.

2.1 Particle Fabrication

Each fuel rod contained test fissile particles, Biso-coated ThO_2 fertile particles, and Triso-coated inert particles. The inert particles were included to minimize irradiation-induced shrinkage (due to the Triso-coating) and, hence, to improve temperature control.

Two batches of Triso-coated fissile particles, one having a WAR Amberlite* IRC-72 resin kernel and the other having a WAR Duolite†

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*Trade name of Rohm and Haas.

†Trade name of Diamond Shamrock Co.

Fig. 1. Configuration for HRB-13.

C-464 resin kernel, were prepared from as-received resin. Each was shape-separated into four fractions varying from near sphericity to large deviations from sphericity. Only one batch of Biso-coated ThO_2 particles (J-489) was used throughout the capsule to help eliminate confusion in interpreting the postirradiation examination results. All the ORNL-coated particles were heat-treated at 1800°C before incorporation into fuel rods. The physical characteristics of the ORNL-coated particles are given in Table 1, and the coating conditions are given in Table 2.

Each of the eight fissile particle fractions was analyzed for particle shape by quantitative image analysis. The deviations from sphericity of the Amberlite type ranged from 9.6 to 29.7%, and those of the Duolite type ranged from 9.6 to 15.8%. Specific shape characteristics for each of the particle fractions are given in Table 3. Radiographs from each particle fraction are shown in Figs. 2 through 9.

2.2 Fuel Rod Fabrication

The fissile, fertile, and inert particles were incorporated into fuel rods before irradiation for all ORNL positions. The matrix for each rod consisted of 55 wt % GLCC* 1074 graphite powder, 30 wt % Ashland† A240 pitch, and 15 wt % Thermax‡ carbon black. The particles were slurry-blended with the matrix materials, after which the mix was granulated, poured into a steel mold, and pressed at 135°C and 4.1 MPa (600 psi). Specimens were fabricated with a central 2.29-mm-diam (0.90-in.) hole. (Original plans called for a platinum vs molybdenum centerline thermocouple; however, because of the chemical interaction observed in HRB-11, it was removed before irradiation.) Specimens were then carbonized vertically in a packed bed of natural flake graphite at 900°C and a heating rate of 90°C/h . They were then heat-treated at 1800°C for 30 min for dimensional stability.

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*Trade name of Great Lakes Carbon Co.

†Trade name of Ashland Oil Co.

‡Trade name of R. T. Vanderbilt Co.

Table 1. Characteristics of particles used in HRB-13

Particle type	Particle batch number			
	OR-2549-H Triso WAR-A ^a	OR-2565-H Triso WAR-D ^b	J-489 Biso ThO ₂	OR-2323-H Triso inert
Kernel composition	UC _{4.640} 1.36	UC _{5.040} 1.31	ThO ₂	Carbon
Kernel diameter, μm	352.9	415.1	496.8	326.9
Standard deviation, %	27.7	27.19	2.2	18.2
Kernel density, Mg/m^3	3.19	2.511	9.95	1.42
Buffer coating thickness, μm	55.0	55.5	74.7	105.3
Standard deviation, %	8.34	7.68	13.8	11.9
Buffer density, Mg/m^3	1.13	1.15	1.168	0.86
ILTI ^c coating thickness, μm	33.9	35.3	76.9	55.3
Standard deviation, %	3.47	2.59	5.3	5.8
ILTI density, Mg/m^3	1.931	1.946	1.904	1.95
SiC coating thickness, μm	30.9	33.4		42.6
Standard deviation, %	1.46	1.31		3.8
SiC density, Mg/m^3	3.201	3.207		3.204
OLTI ^d coating thickness, μm	30.7	33.2		43.5
Standard deviation, %	2.29	3.29		3.7
OLTI density, Mg/m^3	2.018	2.008		2.0

^aWeak-acid resin made with Amberlite IRC-72 resin.

^bWeak-acid resin made with Duolite C-464 resin.

^cILTI, inner low-temperature isotropic.

^dOLTI, outer low-temperature isotropic.

Table 2. Deposition conditions for fissile and fertile particles for HRB-13

Layer	Coating gas	Temperature, °C		Deposition rate, $\mu\text{m/min}$		
		Fissile	J-469	OR-2549-H	OR-2565-H	J-489
Buffer	C ₂ H ₂	1125	1350	6.67	6.25	22.98
ILTI ^a	MAPP ^b	1275		2.19	2.00	
SiC	CH ₃ SiCl ₃	1550		0.20	0.20	
OLTI ^c	MAPP	1275		3.12	3.02	
	C ₃ H ₆		1350			5.83

^aILTI, inner low-temperature isotropic.

^bMAPP, mixture of methylacetylene-propadiene, propane, butane, isobutane, propylene, and butadiene.

^cOLTI, outer low-temperature isotropic.

Table 3. Shape characteristics of fissile particles
in irradiation capsule HRB-13^a

	Diameter, μm		Ratio	Area (μm^2)	Perimeter (μm)	Shape factor ^b	Ratio ^c	Deviation from sphericity (%)
	Minimum	Maximum						
Sample NYE OR-2549-H-3G (101 kernels, 99 particles)								
Kernel	0.368	0.379	1.030	0.108	1.221	0.072	0.905	9.6
Coated particle	0.580	0.593	1.024	0.272	1.938	0.072	0.905	
Sample NYA OR-2549-H-2R (104 kernels, 101 particles)								
Kernel	0.332	0.371	1.112	0.094	1.152	0.069	0.867	13.3
Coated particle	0.584	0.588	1.073	0.251	1.869	0.071	0.892	
Sample NYW OR-2549-H-1RC (117 kernels, 112 particles)								
Kernel	0.284	0.324	1.121	0.072	0.991	0.068	0.854	14.6
Coated particle	0.511	0.559	1.089	0.223	0.761	0.071	0.892	
Sample NYX OR-2549-H-1RR (108 kernels, 102 particles)								
Kernel	0.391	0.503	1.294	0.134	1.540	0.056	0.704	29.7
Coated particle	0.563	0.697	1.243	0.295	2.100	0.066	0.829	
Sample NPG OR-2565-H-1GG (101 kernels, 98 particles)								
Kernel	0.412	0.431	1.045	0.138	1.383	0.072	0.905	9.6
Coated particle	0.637	0.664	1.043	0.334	2.149	0.072	0.905	
Sample NPE OR-2565-H-1GR (115 kernels, 111 particles)								
Kernel	0.422	0.479	1.133	0.154	1.476	0.070	0.880	12.1
Coated particle	0.631	0.705	1.119	0.348	2.206	0.071	0.892	
Sample NPF OR-2565-H-1RG (108 kernels, 102 particles)								
Kernel	0.423	0.503	1.190	0.160	1.518	0.069	0.867	13.3
Coated particle	0.626	0.727	1.165	0.355	2.244	0.070	0.880	
Sample NPD OR-2565-H-1RR (106 kernels, 106 particles)								
Kernel	0.426	0.511	1.202	0.161	1.537	0.067	0.842	15.8
Coated particle	0.626	0.721	1.155	0.350	2.253	0.070	0.880	

^aAll values are based on average measurements.

^bShape factor formula = area/perimeter²; for perfectly spherical particles this value = $\pi^2/(2\pi)^2 = 0.0796$.

^cRatio = calculated shape factor/0.0796.

Fig. 2. Particle batch OR-2549-H-3G located in rods 15 and 16.

Fig. 3. Particle batch OR-2549-H-2R located in fuel rods 1, 2, 11, 12, 19, and 20.

Fig. 4. Particle batch OR-2549-H-IRG located in fuel rods 5, 6, 9, and 10.

Fig. 5. Particle batch OR-2549-H-IRR located in fuel rods 7, 8, 17, and 18.

Fig. 6. Particle batch OR-2565-H-1GG located in fuel rods 25 and 26.

Fig. 7. Particle batch OR-2565-H-1GR located in fuel rods 3, 4, 13, 15, 21, and 22.

Fig. 8. Particle batch OR-2565-H-1RG located in fuel rods 31, 32, 35, and 36.

Fig. 9. Particle batch OR-2565-H-1RR located in fuel rods 23, 24, 33, and 34.

The specimens were characterized by dimensional measurements, weight, radiography, metallography, and photography. They were all nominally 12.5 mm in diameter and 10 mm long (0.49 by 0.39 in.). All had a 2.20-mm-diam (0.090-in.) central hole. An identification mark was formed on one end of each specimen for orientation so that the specimen dimensions could be measured at the same location both before and after irradiation. The dimensions and the heavy-metal loadings for each specimen are shown in Table 4.

2.3 Capsule Loading Scheme

The capsule loading scheme and the objective for each position are presented in Table 5. Of the 40 fuel rod specimens [each nominally 9.84 m long and 12.45 mm in diameter (0.388 by 0.490 in.)], LASNL specimens occupied a space equivalent to eight rods, or 20% of the stack length.

3. CAPSULE OPERATION

Irradiation capsule HRB-13 was installed in the PB-13 (VXF-13) facility of HFIR on November 15, 1976, at the beginning of cycle 140. The reactor was started up slowly during cycle 140 to minimize the impact of the high fission heat rates, which usually occur in fully enriched fissile particles at the beginning of an HRB experiment. The reactor power began at 68 MW and gradually increased to 100 MW after 24 d, at which time sufficient reactivity was left in the HFIR core to operate for 3 d at 100 MW. During this initial irradiation cycle the capsule sweep gas was maintained at 100% He.

Capsule HRB-13 was removed from the HFIR on November 23, 1977, after having completed 14 full HFIR cycles (4 cycles in the permanent beryllium facility and 10 cycles in the removable beryllium facility) for a total operating time of 7721 h at full reactor power of 100 MW (Table 6). The operating temperature in HRB-13 continued to increase during the last two cycles; therefore, the sweep gas was kept at 100% He during that period. The estimated peak centerline temperature for the last cycle was 1325°C

Table 4. Dimensions and heavy-metal loadings for ORNL fuel specimens in irradiation capsule HRB-13

Specimen location ^a	Average diameter ^b		Average length		U per specimen (g)	Loading, Mg/m ³	
	(mm)	(in.)	(mm)	(in.)		²³⁵ U	Th
1	12.410	0.4886	9.934	0.3911	0.0526	0.0421	0.5666
2	12.395	0.4880	9.837	0.3873	0.0526	0.0426	0.5736
3	12.423	0.4891	9.842	0.3875	0.0472	0.0381	0.5365
4	12.436	0.4896	9.756	0.3841	0.0472	0.0383	0.5401
5	12.413	0.4887	9.733	0.3832	0.0431	0.0352	0.5125
6	12.418	0.4889	9.764	0.3844	0.0431	0.0351	0.5105
7	12.398	0.4881	9.761	0.3843	0.0396	0.0323	0.4897
8	12.426	0.4892	9.804	0.3860	0.0396	0.0320	0.4853
9	12.421	0.4890	10.020	0.3945	0.0361	0.0286	0.4566
10	12.428	0.4893	9.695	0.3817	0.0361	0.0296	0.4713
11	12.416	0.4888	9.931	0.3910	0.0337	0.0269	0.4445
12	12.403	0.4883	9.820	0.3866	0.0337	0.0273	0.4505
13	12.416	0.4888	9.749	0.3838	0.0323	0.0264	0.4383
14	12.413	0.4887	9.929	0.3909	0.0323	0.0259	0.4306
15	12.431	0.4894	9.830	0.3870	0.0313	0.0252	0.4217
16	12.426	0.4892	9.815	0.3864	0.0313	0.0253	0.4227
17	12.428	0.4893	9.820	0.3866	0.0301	0.0243	0.4114
18	12.408	0.4885	9.982	0.3930	0.0301	0.0240	0.4061
19	12.451	0.4902	9.947	0.3916	0.0300	0.0238	0.3939
20	12.428	0.4893	9.807	0.3861	0.0300	0.0243	0.4011
21	12.433	0.4895	9.771	0.3847	0.0300	0.0243	0.4022
22	12.431	0.4894	9.680	0.3811	0.0300	0.0246	0.4062
23	12.443	0.4899	9.718	0.3826	0.0301	0.0245	0.4147
24	12.433	0.4895	9.710	0.3823	0.0301	0.0246	0.4157
25	12.403	0.4883	9.985	0.3931	0.0313	0.0250	0.4171
26	12.416	0.4888	9.746	0.3837	0.0313	0.0255	0.4264
31	12.441	0.4898	9.764	0.3844	0.0361	0.0295	0.4697
32	12.405	0.4884	9.888	0.3893	0.0361	0.0289	0.4611
33	12.408	0.4885	9.870	0.3886	0.0396	0.0319	0.4834
34	12.403	0.4883	9.967	0.3924	0.0396	0.0316	0.4792
35	12.405	0.4884	9.776	0.3849	0.0431	0.0351	0.5109
36	12.416	0.4888	9.977	0.3928	0.0431	0.0344	0.4998

^aSpecimens 27 through 30 and 37 through 40 were Los Alamos Scientific National Laboratory advanced fuels.

^bInside diameter of all specimens is 2.29 mm (0.090 in.).

Table 5. Capsule positions, kernel compositions and types, and objectives of HRB-13 fuel rod specimens

Position in capsule	Kernel composition and type ^a	Batch	Objective
1, 2	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-2R	Single satellite peaks attached to kernels
3, 4	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1GR	Primarily slightly eccentric kernels
5, 6	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-1RG	Multiple and single satellites attached to kernels
7, 8	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-1RR	Clusters of small spheres and irregularly shaped kernels
9, 10	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-1RG	Multiple and single satellites attached to kernels
11, 12	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-2R	Single satellite peaks attached to kernels
13, 14	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1GR	Primarily slightly eccentric kernels
15, 16	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-3G	Kernels meet or exceed reference specification
17, 18	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-1RR	Clusters of small spheres and irregularly shaped kernels
19, 20	WAR-A (UC _{4.64} O _{1.36})	OR-2549-H-2R	Single satellite peaks attached to kernels
21, 22	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1GR	Primarily slightly eccentric kernels
23, 24	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1RR	Irregularly shaped kernels
25, 26	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1GG	Kernels meet or exceed specification
27-30	LASNL experiment		Advanced fuels
31, 32	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1RG	Primarily grossly eccentric kernels
33, 34	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1RR	Irregularly shaped kernels
35, 36	WAR-D (UC _{5.04} O _{1.31})	OR-2565-H-1RG	Primarily grossly eccentric kernels
37-40	LASNL experiment		Advanced fuels

^aWAR-A from Amberlite weak-acid resin; WAR-D from Duolite weak-acid resin.

Table 6. Reactor history during operation of HRB-13

HFIR fuel cycle	Operating facility	Cycle dates		Irradiation time, ^a h	
		Begin	End	In cycle	Total accumulated
140	PB-13	11/15/76	12/14/76	577	577
141	PB-13	12/15/77	01/10/77	568	1145
142	PB-13	01/10/77	02/03/77	576	1721
143 ^b		02/05/77	03/01/77		
144	PB-13	03/02/77	03/26/77	563	2284
145	RB-7	03/27/77	04/20/77	599	2843
146	RB-7	04/20/77	05/13/77	550	3393
147	RB-7	05/14/77	06/06/77	544	3937
148	RB-7	06/06/77	06/29/77	552	4489
149	RB-7	07/02/77	07/24/77	547	5036
150	RB-7	07/25/77	08/17/77	549	5585
151	RB-7	08/19/77	09/11/77	547	6132
152	RB-7	09/11/77	10/04/77	545	6677
153	RB-7	10/06/77	10/29/77	537	7214
154	RB-7	10/30/77	11/23/77	507	7721

^aIrradiation time is given in equivalent hours at 100 MW. Cycle 140 was a slow-startup cycle; during cycle 141 the reactor was operated at 90 or 94 MW.

^bCapsule HRB-13 was removed from the reactor during cycle 143 to facilitate repairs to a leaking secondary gas system.

at the reactor horizontal midplane (details are presented in Sect. 4). A complete summary of fission gas release-to-birth rate ratios (R/B) for gas samples taken during the irradiation is presented in Table 7. These measurements indicate a noticeable increase in the R/B ratios for those samples taken during the last two cycles of operation. This observation will be elaborated on in Sect. 5. Burnup and fluence data summaries for all specimens in HRB-13 are reported in Table 8.

Table 7. Fission gas release-to-birth (R/B) data for capsule HRB-13

Sample ^a	Date	Accumulated irradiation time ^b (h)	Fission gas, R/B				
			⁸⁵ Kr	⁸⁷ Kr	⁸⁸ Kr	¹³⁵ Xe	¹³³ Xe
1	12/10/76	490	6.10×10^{-4}	4.10×10^{-4}	3.30×10^{-4}	3.20×10^{-4}	2.70×10^{-3}
2	01/05/77	1040	1.50	1.00	0.85	0.70	0.10
3	01/27/77	1540	0.83	0.57	0.55	0.36	0.68
4	02/01/77	1660	1.10	0.64	0.70	0.48	0.97
5	03/14/77	2010	0.42	0.28	0.28	0.19	0.23
6	04/01/77	2390	6.30	4.00	4.30	6.10	2.00
7	04/05/77	2490	5.20	3.90	3.30	4.80	1.80
8	05/02/77	3120	3.70	2.40	2.60	2.50	2.10
9	05/11/77	3340	4.50	2.80	3.10	3.20	1.90
10	05/19/77	3510	2.50	1.80	1.50	1.30	0.98
11	05/26/77	3680	Sample did not analyze				
12	05/31/77	3800	3.00	2.10	2.10	1.60	1.50
13	06/10/77	4020	2.00	1.60	1.40	1.00	0.82
14	06/14/77	4120	1.60	1.20	1.20	0.67	0.51
15	06/21/77	4290	1.50	1.20	1.20	0.68	0.86
16	06/28/77	4460	2.20	1.60	1.50	1.10	0.94
17	07/07/77	4620	1.30	1.20	0.90	0.62	0.44
18	07/13/77	4760	1.40	1.10	0.97	0.67	0.45
19	07/20/77	4931	2.30	1.80	1.80	1.20	1.43
20	07/28/77	5102	1.50	1.20	1.10	0.81	0.64
21	08/03/77	5245	1.60	1.30	1.20	0.86	0.85
22	08/11/77	5438	1.80	1.50	1.40	1.00	1.20
23	08/23/77	5836	1.60	1.50	1.30	1.00	0.75
24	09/02/77	5928	2.00	1.70	1.60	1.20	1.30
25	09/08/77	6073	2.30	1.90	1.80	1.60	1.10
26	09/15/77	6224	1.90	1.80	1.60	1.40	1.20
27	09/23/77	6413	1.60	1.60	1.40	1.10	1.10
28	09/29/77	6530	2.10	1.80	1.80	1.50	1.40
29	10/24/77	7173	2.20	1.90	1.90	1.70	2.00
30	11/14/77	7584	3.40	3.00	2.80	2.60	3.00
31	11/21/77	7749	6.20	4.90	4.10	3.40	4.60

^aSamples 1 through 7 were taken with the sweep gas at 100% He, whereas the others were taken at design temperature. Samples 1 through 5 were taken while the capsule was in the PB-13 facility, and the others were taken with the capsule in the RB-7 facility.

^bTime given is equivalent 100-MW reactor power time.

Table 8. Calculated burnup and fast fluence for specimens in capsule HRB-13

Specimen	Calculated burnup, % FIMA ^a									Fluence, neutrons/m ² , >0.18 MeV HTGR		
	235U			238U			232Th			PB-13	RB-7	Total
	PB-13	RB-7	Total	PB-13	RB-7	Total	PB-13	RB-7	Total			
1, 2, 39, 40	60	25	85	0.93	10.5	11.4	0.35	4.2	4.6	2.6 × 10 ²⁴	4.6 × 10 ²⁵	4.9 × 10 ²⁵
3, 4, 37, 38	63	22	85	1.07	12.7	13.8	0.41	5.3	5.7	2.8	5.2	5.5
5, 6, 35, 36	66	20	86	1.26	14.6	15.9	0.49	6.2	6.7	3.1	5.8	6.1
7, 8, 33, 34	68	18	86	1.43	16.3	17.7	0.56	6.9	7.5	3.3	6.3	6.6
9, 10, 31, 32	70	15	86	1.54	17.7	19.2	0.62	7.7	8.3	3.6	6.6	7.0
11, 12, 29, 30	71	16	87	1.69	18.9	20.6	0.68	8.3	9.0	3.8	7.2	7.6
13, 14, 27, 28	72	15	87	1.76	19.4	21.2	0.72	8.6	9.3	3.9	7.5	7.9
15, 16, 25, 26	73	14	87	1.84	20.5	22.3	0.76	9.0	9.8	4.1	7.8	8.2
17, 18, 23, 24	73	14	87	1.88	21.0	22.9	0.78	9.3	10.1	4.1	7.9	8.3
19, 20, 21, 22	74	13	87	1.91	21.3	23.2	0.79	9.5	10.3	4.2	8.1	8.5

^aFIMA, fraction of initial heavy-metal atoms.

4. THERMAL ANALYSIS

As with previous HRB capsules, the thermal analysis for capsule HRB-13 was performed for fuel rods adjacent to the C/A thermocouples. For HRB-13 the C/A thermocouples were located in the graphite sleeve adjacent to fuel rods 3, 7, 13, 20, 21, 28, 29, and 34 (see Fig. 1 for schematic diagram of thermocouple location). Plots of fission power density (kilowatt per foot) versus time for these fuel rods are given in Fig. 10.

4.1 Details of Thermal Analysis

The thermal analysis of capsule 13 was performed with the ECNTRK code.⁵ The procedures used were identical with those used with the last six HRB capsules (see Appendix A in refs. 2 through 4). As before, the thermal analysis of HRB-13 relied heavily on the readings of eight C/A thermocouples located in the graphite sleeve. The locations of the eight C/A thermocouples were verified by x-radiographs of the assembled capsule.

Temperature control in the HRB capsules is maintained by varying the mixture of helium and neon in the sweep gas, which passes between the capsule wall and the graphite sleeve and between the graphite sleeve and the fuel rods. Three parameters are used in calculating the fuel operating temperatures: the graphite sleeve midwall temperature (measured with C/A thermocouples), the fuel rod linear heat rates, and the sweep gas composition. If any two of these parameters are known, the third can be calculated with the ECNTRK code. The graphite midwall temperatures are measured, and the sweep gas composition is switched to pure helium for short periods of time throughout each 23-d HFIR cycle. By this technique, a curve of fuel rod heat rate versus time during each cycle can be drawn (see Fig. 10). Using the curves of fuel rod heat rate versus time and the known graphite midwall temperatures, the composition of the sweep gas can then be calculated for each day during each 23-d HFIR cycle. Knowing all three parameters, we calculated the fuel rod operating temperatures presented in Fig. 10.

Additional data needed for the temperature calculations include the dimensional changes in the fuel rods and in the graphite sleeve as

ORNL-DWG 78-18547

(a)

HRB-13, ROD 3

(b)

ORNL-DWG 78-18556

HRB-13, ROD-20

(e)

ORNL-DWG 78-18565

(g)

HRB-13, ROD 29

(h)

ORNL-DWG 78-18550

(c)

ORNL-DWG 78-18559

(f)

ORNL-DWG 78-18568

Fig. 10. Fission power dens
(a) Rod 3. (b) Rod 7. (c) Rod 13
(g) Rod 29. (h) Rod 34.

ORNL-DWG 78-18550

ORNL-DWG 78-18553

(c)

HRB-13, ROD-13

ORNL-DWG 78-18559

ORNL-DWG 78-18562

(f)

HRB-13, ROD 28

ORNL-DWG 78-18568

Fig. 10. Fission power density versus time for HRB-13 fuel rods.
 (a) Rod 3. (b) Rod 7. (c) Rod 13. (d) Rod 20. (e) Rod 21. (f) Rod 28.
 (g) Rod 29. (h) Rod 34.

functions of time during the capsule irradiation. The swelling shown in the graphite sleeve data in Fig. 11 was assumed to occur linearly with time during the irradiation.

The absence of centerline thermocouples included in the capsules precluded checking the accuracy of the temperature calculations. The precision of the calculation can be checked roughly, however, by comparing the calculated sweep gas compositions for each fuel rod considered in the thermal analysis. The sweep gas composition is calculated from the measured graphite midwall temperature and the curve of fission heat rate versus time. This calculation is made for each fuel rod located adjacent to a C/A thermocouple in the graphite sleeve. The sweep gas composition is constant throughout the capsule; the calculated plots should therefore agree well. These plots are shown in Fig. 12. The agreement is good, giving us confidence in the shape of the plots of heat rate versus time shown in Fig. 10. This indicates that any errors in the calculated fuel temperatures are due only to uncertainties in the thermal conductivity of the fuel rods.

Fig. 11. Graphite sleeve dimensional change as a function of fast neutron fluence.

ORNL-DWG 78-18546

(a)

HRB-13, ROD 3

(b)

ORNL-DWG 78-18555

(d)

HRB-13, ROD-20

(e)

ORNL-DWG 78-18564

(g)

HRB-13, ROD 29

(h)

Fig. 12. Calculated sweep gas composition (percent HE) vs. time from beginning of irradiation (days) for Rod 13. (c) Rod 13. (d) Rod 20. (e) Rod 27. (f) Rod 34.

ORNL-DWG 78-18549

ORNL-DWG 78-18552

(c)

HRB-13, ROD-13

ORNL-DWG 78-18558

ORNL-DWG 78-18561

(f)

HRB-13, ROD 28

ORNL-DWG 78-18567

Fig. 12. Calculated sweep gas compositions. (a) Rod 3. (b) Rod 7. (c) Rod 13. (d) Rod 20. (e) Rod 21. (f) Rod 28. (g) Rod 29. (h) Rod 34.

4.2 Discussion of Thermal Analysis

In contrast to previous HRB capsules, which showed steady power density decreases over the first 60 d of the irradiation as the initial ^{235}U inventory rapidly burned out, HRB-13 was started up slowly and showed power density increases over the first cycle of irradiation and steady decreases in subsequent cycles. Aside from the first cycle, HRB-13 operated like other HRB capsules in that the power density versus time remained relatively constant from cycle to cycle after the first 60 d because the rate of ^{235}U buildup kept the fission concentration approximately constant.

The calculated operating temperatures for HRB-13 are shown in Fig. 13. Three curves are shown for each plot. The lowest curve on each plot is the temperature at the midwall position in the graphite sleeve, the center curve is the temperature at the fuel rod surface, and the highest curve is the temperature at the center of the fuel rod. This experiment was designed for a fuel center temperature of 1250°C . Temperature is controlled by changing the composition of the gas that sweeps through the capsule, which can be varied from 100% He to 100% Ne. Because the power density varies with axial location within the capsule, the temperature of all specimens cannot be kept the same. Therefore, a control thermocouple is chosen, and the temperature of this thermocouple is adjusted (by varying the sweep gas composition) to be consistent with 1250°C fuel center temperature. The temperatures of other fuel rods then vary somewhat around this design temperature, as shown in Fig. 13.

5. POST-IRRADIATION EXAMINATION

5.1 Disassembly and Gross Gamma Scanning

After irradiation the capsule was removed from the HFIR and brought to the High Radiation Level Examination Laboratory (HRLEL) for detailed examination. Before disassembly the capsule was gamma-scanned to check the relative burnup levels and location of the fuel. As shown in Fig. 14, no fuel loading appeared to be unusual, and each fuel rod interface was

ORNL-DWG 78-18548

(a) HRB-13, ROD 3

(b)

ORNL-DWG 78-18557

(d) HRB-13, ROD 20

(e)

ORNL-DWG 78-18569

(g) HRB-13, ROD 34

(h)

ORNL-DWG 78-18551

ORNL-DWG 78-18560

ORNL-DWG 78-18566

Fig. 13. Operating temperature versus time. Lower curve is graphite midwall, middle curve is fuel centerline. (a) Rod 3. (b) Rod 20. (c) Rod 21. (d) Rod 28. (e) Rod 29. (f) Rod 3.

ORNL-DWG 78-18551

ORNL-DWG 78-18554

(c)

HRB-13, ROD-13

ORNL-DWG 78-18560

ORNL-DWG 78-18563

(f)

HRB-13, ROD 28

ORNL-DWG 78-18566

Fig. 13. Operating temperature versus time for HRB-13 fuel rods. Lower curve is graphite midwall, middle curve is fuel surface, and upper curve is fuel centerline. (a) Rod 3. (b) Rod 7. (c) Rod 13. (d) Rod 20. (e) Rod 21. (f) Rod 28. (g) Rod 29. (h) Rod 34.

Fig. 14. Gross gamma scan of capsule before fuel removal.

distinctly clear. The capsule was cut open, and the fuel rods and graphite sleeve were removed without difficulty. After the fuel rods were removed from the graphite sleeve, another gamma scan (Fig. 15) was made of the empty graphite sleeve. High activity was observed adjacent to fuel rods 17 through 40. Detailed gamma scans (presented in Appendix A) showed that the high activities were due to the presence of ^{134}Cs , ^{137}Cs , and ^{144}Ce and that lower activities of $^{110\text{m}}\text{Ag}$, ^{154}Eu , and ^{233}Pa were also detected.

5.2 Visual Examination

After the fuel rods were removed from the graphite sleeve, the surfaces were examined. Figure 16 shows the general appearances of the rods after irradiation. Although the rods remained intact, detailed examination showed numerous failed particles on the surfaces. The results are summarized in Table 9 for all the ORNL rods. Failed particles were visible for all particle types including the reference designs (i.e., the Amberlite and Duolite resins with 9.6% deviation from sphericity). The

Fig. 15. Gross gamma scan of empty graphite sleeve.

greatest number of surface failures was with the Amberlite resin having a spherical deviation of 29.7%. Further discussions of these failures are presented in Sects. 5.4 and 5.5.

5.3 Dimensional Inspection

Postirradiation dimensional measurements of the fuel rods and graphite sleeve were made and compared with preirradiation measurements. The results on the fuel rods are presented in Table 10. These measurements were used in the thermal analysis of the capsule (Sect. 4.1). The dimensional changes as a function of fast neutron fluence (>0.18 MeV) are shown in Figs. 11 and 17.

5.4 Gamma Analysis of Fissile Particles

Selected fuel rods were electrolytically deconsolidated⁶ and examined with the irradiated microsphere gamma analyzer (IMGA) system.⁷ (Additional details on the deconsolidation are given in Appendix B).

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Fig. 16. Visual appearance of fuel rods after irradiation. Fuel rod numbers appear below the appropriate specimens.

Table 9. Results of visual examination of fuel rod surfaces from HRB-13

Fissile particle deviation from sphericity (%) ^a	Position	Number of surface failures	Total failures	Fast fluence (neutrons/cm ² , >0.18 MeV) HTGR
<i>Amberlite</i>				
9.6	15	2	5	8.2 × 10 ²⁵
9.6	16	3		
13.3	1	0	2	4.9
13.3	2	2		
13.3	11	7	10	7.6
13.3	12	3		
13.3	19	2	5	8.5
13.3	20 ^b	3		
14.6	5	3	6	6.1
14.6	6	3		
14.6	9	8	13	7.0
14.6	10	5		
29.7	7	16	42	6.6
29.7	8	26		
29.7	17	11	28	8.3
29.7	18	17		
<i>Duolite</i>				
9.6	25	0	2	8.2
9.6	26	2		
12.1	3	4	8	5.5
12.1	4	4		
12.1	13	6	10	7.9
12.1	14	4		
12.1	21	6	10	8.5
12.1	22	4		
13.3	31	0	1	7.0
13.3	32	1		
13.3	35	2	3	6.6
13.3	36	1		
15.8	23	14	18	8.3
15.8	24	4		
15.8	33	6	9	6.1
15.8	34	3		

^aDeviation from sphericity (%) = $100[1 - 4\pi \times \text{cross sectional area of kernel}/(\text{perimeter of kernel})^2]$.

^bPeak fluence (horizontal midplane of the reactor).

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Fig. 17. Fuel rod dimensional changes as a function of fast neutron fluence.

Gamma spectra from individual particles were taken, and ratios of volatile-to-stable fission products were calculated (e.g., $^{137}\text{Cs}/^{95}\text{Zr}$). These ratios have been shown to be an accurate monitor of volatile fission product release; retention from the individual particle indicates whether or not the particle has failed.^{8,9}

Summaries of the $^{137}\text{Cs}/^{95}\text{Zr}$, $^{134}\text{Cs}/^{137}\text{Cs}$, $^{144}\text{Ce}/^{95}\text{Zr}$, and $^{137}\text{Cs}/^{106}\text{Ru}$ ratios are given in Tables 11 through 14. As shown by the mean fraction of the observed-to-calculated ratio for $^{137}\text{Cs}/^{95}\text{Zr}$, fission product loss occurred from each of the particle batches examined.

The $^{137}\text{Cs}/^{95}\text{Zr}$ ratio has been determined to be the best indicator of SiC integrity and failure fraction determinations.^{10,11} The histograms for the $^{137}\text{Cs}/^{95}\text{Zr}$ ratio from each fuel rod examined are shown in Figs. 18 through 31.

As shown in the histograms, failed particles (where loss of ^{137}Cs has occurred) are located to the left of the distributions of particles located about the theoretical ratio. The failure fractions for each batch of particles examined are shown in Table 11.

In every fuel rod examined, fissile particle failures were presented; in some cases the failure fractions were well over 50% of those examined. These high-failure fractions were also found for the reference particles

Table 11. Summary of irradiated microsphere gamma analyzer results on $^{137}\text{Cs}/^{95}\text{Zr}$ ratio

Position	Number of particles	$^{137}\text{Cs}/^{95}\text{Zr}$ Ratio			Standard deviation (%)	Fraction of theoretical (%)	Failed particles	
		Minimum	Maximum	Mean			(%)	(Number)
2	337	7.907×10^{-4}	8.697×10^{-2}	7.102×10^{-2}	19.20	77.9	11.3	38
10	224	2.665×10^{-4}	1.246×10^{-1}	5.174×10^{-2}	79.14	49.5	54.9	124
15	381	7.162×10^{-4}	1.095×10^{-1}	5.425×10^{-2}	76.10	49.6	58.8	224
17	119	1.743×10^{-4}	1.087×10^{-1}	4.545×10^{-2}	94.95	41.2	50.4	60
18	117	6.130×10^{-5}	1.073×10^{-1}	3.981×10^{-2}	106.75	37.2	71.8	84
19	333	4.107×10^{-4}	1.112×10^{-1}	5.387×10^{-2}	78.12	48.6	54.4	181
20	289	7.060×10^{-4}	1.101×10^{-1}	5.522×10^{-2}	77.81	49.6	56.4	163
21	176	6.809×10^{-5}	1.149×10^{-1}	8.607×10^{-2}	40.22	77.4	19.9	35
22	194	3.046×10^{-5}	1.143×10^{-1}	8.166×10^{-2}	47.76	73.4	24.2	47
23	133	2.147×10^{-4}	1.155×10^{-1}	7.577×10^{-2}	55.88	68.2	35.3	47
24	222	5.107×10^{-5}	1.111×10^{-1}	7.169×10^{-2}	57.64	64.8	34.2	76
25	171	1.107×10^{-3}	1.136×10^{-1}	9.302×10^{-2}	28.12	84.5	11.7	20
26	193	4.648×10^{-3}	1.104×10^{-1}	9.497×10^{-2}	19.45	86.7	7.0	11
31	180	4.072×10^{-4}	1.069×10^{-1}	9.195×10^{-2}	20.74	87.6	7.8	14

Table 12. Summary of irradiated microsphere gamma analyzer results on $^{134}\text{Cs}/^{137}\text{Cs}$ ratio

Position	Number of particles	$^{134}\text{Cs}/^{137}\text{Cs}$ Ratio			Standard deviation (%)
		Minimum	Maximum	Mean	
2	337	1.837	3.012	2.914	2.93
10	224	1.377	5.922	2.851	11.89
15	381	1.788	2.924	2.640	5.55
18	117	5.545×10^{-1}	2.259×10^1	2.831	68.38
19	333	6.868×10^{-1}	2.973	2.550	7.38
20	289	1.841	2.741	2.545	6.83
21	176	9.699×10^{-1}	1.536×10^1	2.417	41.74
22	194	2.657×10^{-1}	2.088×10^1	2.617	53.14
23	133	1.034	5.141	2.591	14.61
24	222	8.143×10^{-1}	1.873×10^1	2.605	46.49
25	171	1.878	2.802	2.686	3.40
26	193	2.474	2.797	2.713	1.55
31	180	2.601	2.923	2.854	1.76

Table 13. Summary of irradiated microsphere gamma analyzer results on $^{144}\text{Ce}/^{95}\text{Zr}$ ratio

Position	Number of particles	$^{144}\text{Ce}/^{95}\text{Zr}$ Ratio			Standard deviation (%)
		Minimum	Maximum	Mean	
2	337	1.009	1.260	1.093	3.21
10	224	1.160	1.705	1.374	4.29
15	381	1.219	1.537	1.360	2.84
18	117	1.211	1.555	1.402	3.32
19	333	1.055	1.600	1.401	4.35
20	289	1.288	1.625	1.426	3.44
21	176	7.465×10^{-1}	1.492	1.313	5.71
22	194	1.208	1.610	1.432	4.62
23	133	1.217	1.576	1.417	4.44
24	222	5.086×10^{-1}	1.512	1.366	5.72
25	171	1.238	1.622	1.418	4.72
26	193	2.986×10^{-1}	1.551	1.328	7.98
31	180	1.210	1.534	1.372	4.20

Table 14. Summary of irradiated microsphere gamma analyzer results on $^{137}\text{Cs}/^{106}\text{Ru}$ ratio

Position	Number of particles	$^{137}\text{Cs}/^{106}\text{Ru}$ Ratio			Standard deviation (%)
		Minimum	Maximum	Mean	
2	337	6.925×10^{-3}	7.207×10^{-1}	6.292×10^{-1}	19.31
10	224	1.626×10^{-3}	7.809×10^{-1}	3.137×10^{-1}	79.04
15	381	1.754×10^{-3}	2.738×10^{-1}	1.351×10^{-1}	75.79
18	117	3.088×10^{-4}	6.219×10^{-1}	2.058×10^{-1}	107.33
19	333	2.168×10^{-3}	5.910×10^{-1}	2.817×10^{-1}	78.24
20	289	3.801×10^{-3}	5.520×10^{-1}	2.812×10^{-1}	77.58
21	176	3.432×10^{-4}	5.547×10^{-1}	4.415×10^{-1}	40.14
22	194	1.530×10^{-4}	5.618×10^{-1}	4.190×10^{-1}	47.67
23	133	1.087×10^{-3}	5.545×10^{-1}	3.796×10^{-1}	55.82
24	222	2.726×10^{-4}	7.570×10^{-1}	3.979×10^{-1}	57.95
25	171	5.248×10^{-3}	5.805×10^{-1}	4.817×10^{-1}	28.24
26	193	2.389×10^{-2}	6.365×10^{-1}	5.172×10^{-1}	19.40
31	180	2.530×10^{-3}	6.166×10^{-1}	5.410×10^{-1}	20.64

Fig. 18. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-2.

Fig. 19. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-10.

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Fig. 20. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-15.

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Fig. 21. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-17.

Fig. 22. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-18.

Fig. 23. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-19.

Fig. 24. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-20.

Fig. 25. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-21.

Fig. 26. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-22.

Fig. 27. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-23.

Fig. 28. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-24.

Fig. 29. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-25.

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Fig. 30. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-26.

ORNL-DWG 79-20714

Fig. 31. Histogram of $^{137}\text{Cs}/^{95}\text{Zr}$ ratio for HRB-13-31.

(i.e., the batches with 9.6% deviation from sphericity). Although some correlation of failure fraction (and ^{137}Cs release) with deviation from sphericity is evident (see Figs. 32 and 33), Sect. 5.5 shows that the failures resulted from chemical interaction with the SiC coating.

5.5 Metallographic and Electron Microprobe Examination of Fissile Particles

After examination by the IMGA system, particles that had been classified as failed were submitted for metallographic and electron microprobe examination. Representative particles from each batch are shown in Figs. 34 through 42.

Every particle type examined showed that the SiC coatings had suffered chemical attack that resulted in broken and breached coatings. The high failure fractions observed with these particles by the IMGA system were therefore not surprising. In addition, the high R/B values during the irradiation and the numerous broken particles observed during the visual examination were also indicative of the high failure fractions.

Because only two batches of coated fissile particles were actually irradiated (the particles were shape-separated after coating), we estimated that the same chemical interaction would take place in each batch of particles and decided to examine only two samples. The samples examined were from rods RPB-13-17 and HRB-13-24. Both of the samples had shown high failure fractions during the IMGA examination.

Fuel rod HRB-13-24 contained fissile particles made from Duolite resin with a 15.8% deviation from sphericity. The electron microprobe (see Fig. 43) showed that the area of SiC corrosion contained uranium, palladium, and chlorine with a trace of the rare earths (typified by neodymium). Evidently, chlorine was introduced into the particle during deposition of the SiC coating. Chlorine has been responsible for heavy-metal transport and SiC corrosion in previous irradiation tests,^{12,13} and it is believed to be the cause of this SiC corrosion.

Examination of the particles from HRB-13-17 (made of Amberlite resin and having a 29.7% deviation from sphericity) showed that these particles also contained chlorine (Fig. 44). In the SiC corrosion areas, palladium

Fig. 32. Failure fraction as a function of deviation from sphericity.

Fig. 33. Release of ^{137}Cs as a function of deviation from sphericity for HRB-13.

Fig. 34. Representative fissile particles from OR-2549-H-2R irradiated in fuel rod 2; (a) and (c), bright field; (b) and (d), polarized light.

Fig. 35. Representative fissile particles from OR-2549-H-IRC irradiated in fuel rod 10; (a) and (c), bright field; (b) and (d), polarized light.

Fig. 36. Representative fissile particles from OR-2549-H-3G irradiated in fuel rods 15 and 16; (a) and (c), bright field; (b) and (d), polarized light. Particle in (a), from rod 16; particle in (c), from rod 15.

Fig. 37. Representative fissile particles from OR-2549-H-1RR irradiated in fuel rods 17 and 18; (a) and (c), bright field; (b) and (d), polarized light. Particles shown are from rod 18.

Fig. 38. Representative fissile particles from OR-2549-H-2R irradiated in fuel rods 19 and 20; (a) and (c), bright field; (b) and (d), polarized light. Particles shown are from rod 19.

Fig. 39. Representative fissile particles from OR-2549-H-1GR irradiated in fuel rods 21 and 22; (a) and (c), bright field; (b) and (d), polarized light. Particle shown in (a) is from rod 21; particle shown in (c) is from rod 22.

Fig. 40. Representative fissile particles from OR-2549-H-IRR irradiated in fuel rods 23 and 24; (a) and (c), bright field; (b) and (d), polarized light. Particles shown are from rod 23.

Fig. 41. Representative fissile particles from OK-2549-H-1GG irradiated in fuel rods 25 and 26; (a) and (c), bright field; (b) and (d), polarized light. Particles shown are from rod 25.

Fig. 42. Representative fissile particles from OR-2549-H-IRR irradiated in fuel rod 31; (a) and (c), bright field; (b) and (d), polarized light.

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Fig. 43. Electron microprobe x-rays of typical fuel particle from rod HRB-13-24. (a) Back-scattered electron image. (b) U $M\beta$. (c) Nd $L\alpha$. (d) Zr $L\alpha$. (e) Pd $L\alpha$. (f) Cl $K\alpha$.

Y-172382

Fig. 44. Electron microprobe x-rays of fuel particle from rod HRB-13-17.
(a) Backscattered electron image. (b) Si $K\alpha$. (c) Pd $L\alpha$. (d) Cl $K\alpha$.

was observed; however, in contrast to HRB-13-24, only trace amounts of uranium and no rare earths were found. Again it is believed that the chlorine contamination is the source of the high failure fractions observed.

Aside from the chemical attack of the SiC coating, the metallography showed that, for the most part, the misshapen kernels behaved like typical WARs irradiated in previous tests. All showed densification and phase segregation typical for particles with their oxygen content. In some cases, where the original particle contained a kernel with other "satellite" kernels attached, the kernels densified separately (Fig. 35). However, for the majority of the particles observed, all kernels appeared to densify into one "main" kernel.

6. CONCLUSIONS

The objective of the ORNL portion of the HRB-13 experiment was to provide definitive results on how variously misshapen kernels affect the irradiation performance of the WAR-derived fissile fuel particle. The fuel produced and irradiated ranged from nearly spherical to grossly misshapen and multisphere particles.

When the fuel particles were examined after irradiation, high failure fractions were observed in all specimens. Gamma analysis of the individual particles showed that the failure fractions ranged from 7 to 72%. Even the lowest failure fraction is well above those considered to be acceptable. Examination by metallography and electron microprobe showed that the particles contained chlorine introduced during coating of the SiC. As a result, the particles suffered severe corrosion of the SiC with subsequent fission product release during irradiation. There was some correlation of increasing failure fraction (also increasing ^{137}Cs release) with increasing deviation from sphericity. However, because all particles were affected by the SiC corrosion, no definitive conclusions were reached.

In addition, by the time the HRB-13 experiment was examined, the highly enriched uranium fuel cycle was no longer being considered for use with the HTGR. Consequently, interest in the low-density WAR kernels was diminished.

7. ACKNOWLEDGMENTS

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Appendix A

DETAILED GAMMA SCANS OF EMPTY GRAPHITE SLEEVE

Gamma spectra from the empty graphite sleeve are tabulated in this appendix. The spectra were acquired by use of a collimator 0.48 cm in diameter by 43.2 cm long. The graphite sleeve was placed in an aluminum tube and spectra taken on the gross scan of the empty sleeve.

Definitions for the column headings used are

F. P.	The chemical symbol and isotope number of all emitters that are identified with the peak.
ENERGY (KEV)	The energy (in keV) that corresponds to the peak centroid.
PEAK CHNL	The channel number of the peak centroid (not the channel containing the peak number of counts).
CPS	The rate (counts per second) at which characteristic gamma rays having the centroid energy are detected via a full energy mechanism.
GAMMA/SEC	The CPS corrected for amplified pulse pileup losses.
ERR (%)	An estimate of the statistical uncertainty (due to the random nature of the radioactive decay process) in the measurement of CPS (and therefore in GAMMA/SEC). The best interpretation is to assume that there is a 68% probability that the true value of CPS deviates from the listed value by less than the listed error.
BASE WIDTH	The number of histogram channels involved in the calculation of CPS.
MU	The order of the multiplet that includes the listed peak. This number includes all local maxima detected in the base width even though some of them may not have satisfied the necessary criteria for being listed as separate peaks.
FWHM (KEV)	The peak's full width at half maximum (FWHM) in keV. This number is useful for spotting unresolved multiplets, which often have abnormally high FWHMs. If the program cannot

calculate the FWHM (which, for example, sometimes occurs for the central peak of a triplet), a zero will be printed in this column.

PK   A sequential number assigned to each peak.

Additional information is given below to clarify the tabulations of gamma spectra in this appendix.

1. The symbol "???" under P.P. indicates that a peak was located at the energy listed but that this peak was not in the library of long-lived fission product gamma peaks. Such peaks are due to (1) activation products from contamination in the graphite (e.g., ^{125}Sb and ^{46}Sc), (2) short-lived fission products not listed in the library (e.g., ^{156}Eu , ^{140}La , and ^{140}Ba), (3) cell background (^{60}Co), and (4) fluorescent x rays (e.g., Pb).

2. The number at the top of each spectrum listing is the time (24-h system) and day the spectrum was acquired (i.e., 1516.14 is 3:16 PM).

3. The number of peaks listed for the various scans is not constant. The same peak-searching procedure was used in all scans, but the number of peaks varied with the number of fission products present and their concentration. The concentration of fission products, in turn, depends on burnup release from the fuel rods and the elapsed time since discharge from the reactor.

4. Some lines have a fission product listed but no other entries (e.g., the ^{155}Eu peak between 88.11 and 93.86 keV on the first scan). This means that the peak for this fission product is very close to the peak of the fission product just ahead of it in the listing (^{233}Pa in the example given) and that resolution of the two peaks was not possible. Therefore, both peaks that may contribute to the CPS at the particular energy are listed.

Gamma Spectra Acquired from Empty Sleeve of Capsule HRB-13

2 -17 -1978 1516.14
 HRB-13 SLEEVE, POS. # 1; 3/16 X17 IN. HOLE

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CE144	79.33	113.33	23.223	3.276E+01	7.14	8	1	1.80	1
PA233	85.58	122.25	15.883	2.214E+01	8.14	24	4	1.48	2
EUI55									
PA233	88.11	125.87	34.976	4.856E+01	4.69	24	4	2.11	3
EUI55									
PA233	93.86	134.09	10.932	1.504E+01	10.42	24	4	2.94	4
PA233	97.63	139.47	15.777	2.158E+01	8.15	24	4	1.93	5
EUI55	104.43	149.18	9.4200	1.275E+01	19.01	9	1	2.18	6
PA233									
EUI54	122.33	174.75	25.615	3.415E+01	7.38	9	1	1.93	7
CE144	132.75	189.65	253.96	3.361E+02	1.04	11	1	1.83	8
CE141	144.80	206.86	18.795	2.468E+01	10.15	10	1	1.88	9
PA233	299.71	428.15	5.2775	6.576E+00	24.90	7	1	2.14	10
PA233	311.47	444.96	29.280	3.639E+01	5.74	9	1	1.94	11
PA233	340.27	486.09	7.4050	9.154E+00	16.07	6	1	1.95	12
CS134	475.24	678.91	11.253	1.363E+01	11.76	8	1	2.13	13
CS134	563.15	804.51	52.719	6.328E+01	2.65	19	2	2.05	14
CS134	569.21	813.16	99.723	1.196E+02	1.91	19	2	2.06	15
CS134	604.69	863.85	585.85	7.005E+02	0.50	12	1	2.09	16
???	646.35	923.35	9.4400	1.124E+01	9.30	8	1	2.21	17
CS137	661.57	945.10	187.79	2.234E+02	1.11	18	3	1.95	18
CE144	696.53	995.05	9.1275	1.083E+01	8.43	9	1	1.96	19
Z995	723.72	1033.89	16.085	1.904E+01	4.94	9	1	2.35	20
EUI54									
Z995	756.77	1081.10	6.1650	7.283E+00	11.56	9	1	2.25	21
EUI54									
NB95	765.93	1094.19	15.220	1.797E+01	5.22	9	1	2.05	22
AG110M									
CS134	795.98	1137.12	414.63	4.885E+02	0.56	21	2	2.15	23
CS134	802.12	1145.88	40.475	4.767E+01	2.03	21	2	2.19	24
???	812.00	1160.00	10.280	1.210E+01	6.89	10	1	2.11	25
???	818.72	1169.60	3.4650	4.077E+00	12.76	6	1	1.76	26
RUI06	873.75	1248.22	1.8250	2.140E+00	28.38	9	1	1.91	27
EUI54									
EUI54	996.42	1423.46	1.3200	1.538E+00	25.88	6	1	1.56	28
CS134	1039.35	1484.78	4.7350	5.505E+00	8.29	7	1	2.14	29
RUI06	1048.53	1497.91	3.0600	3.556E+00	12.56	8	1	2.70	30
???	1065.54	1522.20	4.9325	5.728E+00	8.75	9	1	2.38	31
???	1079.57	1542.24	4.0725	4.727E+00	10.76	9	1	2.34	32
???	1154.29	1648.98	10.690	1.236E+01	4.77	11	1	2.62	33
CS134	1168.40	1669.15	5.6408	6.523E+00	8.26	16	2	2.12	34
???	1173.77	1676.81	1.9791	2.288E+00	14.58	16	2	2.36	35
???	1231.25	1758.93	6.3475	7.323E+00	7.57	13	2	2.48	36
???	1243.09	1775.85	5.9325	6.841E+00	5.84	9	1	2.32	37
EUI54	1274.99	1821.41	1.8300	2.107E+00	18.34	7	1	1.65	38
???	1332.78	1903.98	1.9400	2.230E+00	15.18	9	2	2.28	39
CS134	1365.85	1951.22	1.0700	1.228E+01	4.06	12	1	2.74	40

2 -17 -1978 1519.53
 HR3-13 SLEEVE, POS.# 2; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GA.14A/SEC	ERR (%)	BW	MJ	FWHM (KEV)	PK #
CE144	79.34	113.34	22.050	3.020E+01	6.06	8	1	1.79	1
PA233	86.10	122.99	16.530	2.235E+01	5.79	12	2	2.16	2
EJ155									
PA233	88.11	125.87	30.449	4.103E+01	4.02	12	2	2.30	3
EJ155									
PA233	93.94	134.20	11.129	1.486E+01	9.61	14	2	1.94	4
PA233	97.70	139.58	17.913	2.378E+01	7.17	14	2	1.85	5
EJ155	104.62	149.46	12.150	1.596E+01	10.62	8	1	2.02	6
PA233									
TE125	110.48	157.83	9.0025	1.177E+01	18.50	11	2	2.31	7
PA233									
EJ154	122.42	174.88	23.822	3.083E+01	6.31	9	1	1.71	8
CE144	132.89	189.84	236.65	3.040E+02	0.94	11	1	1.82	9
CE141	144.84	206.91	23.205	2.958E+01	6.66	11	2	1.99	10
???	198.80	284.00	2.6850	3.338E+00	32.02	6	1	1.43	11
PA233	299.58	427.97	6.1900	7.487E+00	15.34	8	1	1.88	12
PA233	311.55	445.07	33.030	3.985E+01	3.52	9	1	1.93	13
???	487.13	695.90	1.9750	2.320E+00	30.50	6	1	1.51	14
CS134	563.33	804.76	12.650	1.474E+01	6.18	19	2	2.30	15
CS134	569.25	813.21	22.709	2.644E+01	4.60	19	2	2.34	16
CS134	604.78	863.97	141.34	1.640E+02	1.23	17	2	2.34	17
???	646.36	923.37	9.4500	1.092E+01	6.45	8	1	1.98	18
CS137	661.73	945.32	41.755	4.822E+01	2.26	10	1	2.31	19
CE144	696.61	995.15	8.7200	1.004E+01	6.36	8	1	2.33	20
???	709.41	1013.44	7.7900	9.090E-01	40.73	5	1	1.28	21
ZR95	723.83	1034.04	14.652	1.684E+01	4.70	11	1	2.21	22
EJ154									
ZR95	756.96	1081.37	5.6925	6.528E+00	9.07	9	1	2.12	23
EJ154									
NB95	765.93	1094.18	15.715	1.801E+01	3.98	10	1	2.14	24
AG110M									
CS134	796.05	1137.21	97.533	1.115E+02	1.22	19	2	2.13	25
CS134	802.23	1146.05	9.4614	1.081E+01	4.58	19	2	2.12	26
???	812.05	1160.07	12.245	1.376E+01	4.53	9	1	2.02	27
???	867.48	1239.25	1.6450	1.873E+00	18.27	6	1	2.14	28
RU106	873.26	1247.51	2.2400	2.550E+00	16.27	8	1	1.91	29
EJ154									
???	961.14	1373.06	1.9475	2.206E+00	15.26	7	1	2.45	30
EJ154	996.54	1423.63	1.5600	1.764E+00	17.97	6	1	1.37	31
EJ154	1005.19	1435.99	2.6000	2.939E+00	14.54	9	1	1.83	32
???	1065.44	1522.06	4.9925	5.62E+00	7.25	9	1	2.55	33
???	1079.86	1542.66	3.9025	4.396E+00	9.51	9	1	2.36	34
???	1154.27	1648.96	10.315	1.158E+01	4.04	10	1	2.47	35
???	1231.25	1758.93	7.1000	7.951E+00	5.82	15	2	2.26	36
???	1243.12	1775.89	5.6950	6.374E+00	5.64	10	1	2.34	37
EJ154	1276.10	1823.00	6.9175	7.734E+00	5.35	13	1	4.95	38
CS134	1366.17	1951.67	3.4925	3.893E+00	7.96	11	1	3.10	39

2 -17 -1978 1523.25
H9B-13 SLEEVE, POS.# 3; 3/16 X 17 IN. HOLE, S-TJ-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CE144	79.41	113.44	16.177	2.212E+01	8.54	9	1	1.93	1
PA233	86.13	123.84	15.751	2.127E+01	5.81	12	2	2.54	2
EUI55									
PA233	88.88	125.84	29.688	3.995E+01	4.88	12	2	2.88	3
EUI55									
PA233	93.88	134.11	12.116	1.616E+01	8.41	14	2	1.98	4
PA233	97.83	139.75	20.333	2.695E+01	6.17	14	2	2.81	5
EUI55	104.44	149.21	9.8508	1.292E+01	12.49	8	1	2.21	6
PA233									
TE125	110.14	157.35	10.378	1.354E+01	15.53	11	2	2.12	7
PA233									
EUI54	122.31	174.73	23.662	3.858E+01	6.86	9	1	1.66	8
CE144	132.89	189.85	167.82	2.152E+02	1.21	11	1	1.88	9
CE141	144.84	206.91	20.845	2.653E+01	6.18	9	1	1.85	10
???	198.97	284.25	3.7758	4.687E+00	22.81	6	1	1.56	11
PA233	299.73	428.18	7.4858	9.040E+00	11.31	7	1	1.79	12
PA233	311.58	445.11	36.815	4.435E+01	3.38	10	1	1.82	13
PA233	340.27	486.10	4.2000	5.033E+00	21.59	8	1	1.40	14
CS134	563.28	804.69	11.424	1.329E+01	6.42	18	2	2.06	15
CS134	569.29	813.27	22.660	2.635E+01	4.48	18	2	2.84	16
CS134	604.78	863.97	137.71	1.596E+02	1.35	20	3	2.12	17
???	646.29	923.27	9.5675	1.134E+01	6.76	9	1	2.29	18
AG110M	657.89	939.84	2.9922	3.452E+00	12.25	14	2	2.89	19
CS137	661.68	945.26	42.617	4.915E+01	2.82	14	2	2.14	20
CE144	696.65	995.22	5.8500	5.888E+00	18.12	8	1	1.81	21
ZR95	723.84	1034.05	15.925	1.828E+01	4.88	10	1	2.30	22
EUI54									
ZR95	756.84	1081.28	6.4988	7.432E+00	8.58	10	1	2.31	23
EUI54									
NB95	765.92	1094.17	16.348	1.878E+01	3.95	10	1	2.16	24
AG110M									
CS134	796.05	1137.21	93.719	1.878E+02	1.24	19	2	2.23	25
CS134	802.17	1145.95	8.8958	1.015E+01	4.78	19	2	1.93	26
???	812.82	1160.82	11.618	1.324E+01	5.16	11	1	2.83	27
???	867.59	1239.42	1.4175	1.612E+00	29.33	9	1	1.59	28
AG110M	884.93	1264.18	1.6258	1.846E+00	15.71	5	1	1.52	29
???	944.54	1349.34	1.4158	1.682E+00	19.96	6	1	1.59	30
???	961.12	1373.03	2.2225	2.514E+00	13.21	7	1	2.23	31
EUI54	996.48	1423.54	2.1954	2.479E+00	14.98	19	3	1.88	32
EUI54	1005.19	1435.99	3.2395	3.657E+00	12.52	19	3	2.32	33
???	1065.61	1522.38	4.5788	5.145E+00	8.89	10	1	2.16	34
???	1079.92	1542.74	5.5788	6.266E+00	6.88	12	2	2.28	35
???	1154.38	1649.88	10.982	1.231E+01	3.96	11	1	2.34	36
CS134	1168.51	1669.38	1.1458	1.283E+00	19.18	6	1	2.23	37
???	1231.29	1758.98	7.1825	7.942E+00	4.51	9	1	2.48	38
???	1243.12	1775.88	5.9758	6.679E+00	5.59	10	1	2.52	39
EUI54	1275.11	1821.58	2.8358	2.272E+00	13.83	6	1	1.81	40
CS134	1366.48	1952.11	3.6388	4.848E+00	6.89	9	1	3.17	41

2 -17 -1978 1527-06
 H9B-15 SLEEVE, POS. # 4; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BV	MU	FYHM (KEV)	PK #
PA233	93.91	134.16	9.3856	1.240E+01	8.67	13	2	1.87	1
PA233	97.69	139.56	15.421	2.026E+01	6.28	13	2	1.93	2
TE125	110.12	157.32	3.5900	4.646E+00	28.49	8	1	1.60	3
PA233									
CE144	133.06	190.08	6.5850	8.368E+00	13.65	7	1	1.87	4
CE141	144.92	207.03	4.4550	5.619E+00	19.66	7	1	1.64	5
PA233	299.73	428.19	4.9375	5.909E+00	15.06	7	1	1.96	6
PA233	311.60	445.14	28.482	3.400E+01	3.44	9	1	1.77	7
PA233	340.19	485.99	3.1550	3.746E+00	19.59	6	1	1.70	8
RU103	496.86	709.80	2.0450	2.374E+00	25.49	7	1	1.66	9
CS134	563.39	804.84	11.361	1.309E+01	5.57	18	2	2.07	10
CS134	569.31	813.30	19.948	2.298E+01	4.09	18	2	1.96	11
CS134	604.78	863.98	119.54	1.372E+02	1.05	11	1	2.08	12
CS137	661.82	945.46	36.342	4.153E+01	2.20	11	1	2.01	13
ZR95	724.35	1034.79	3.5700	4.060E+00	9.49	9	1	2.22	14
EUI54									
ZR95	756.93	1081.33	4.1700	4.731E+00	7.85	8	1	2.05	15
EUI54									
NB95	765.96	1094.23	11.725	1.329E+01	3.92	10	1	2.05	16
AG110M									
CS134	796.10	1137.28	81.962	9.276E+01	1.20	19	2	2.11	17
CS134	802.21	1146.01	8.5579	9.681E+00	4.18	19	2	2.20	18
???	818.75	1169.65	1.1600	1.310E+00	14.83	8	1	1.73	19
AG110M	885.24	1264.63	0.66000	7.429E-01	25.44	8	1	2.23	20
CS134	1039.53	1485.04	0.75000	8.376E-01	19.18	8	2	1.16	21
RU106	1048.78	1498.26	0.63250	7.060E-01	20.27	7	1	2.11	22
CS134	1168.58	1659.39	1.0680	1.186E+00	12.51	13	2	2.16	23
???	1173.20	1676.00	0.43942	4.879E-01	23.17	13	2	1.40	24
CS134	1365.94	1951.35	2.0725	2.285E+00	7.12	11	1	2.83	25
AG110M	1385.19	1978.84	0.25000	2.755E-01	24.33	8	1	2.45	26

2 -17 -1978 1530.53
 HRB-13 SLEEVE, POS. # 5; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
PA233	93.82	134.03	8.0602	1.079E+01	13.54	17	3	1.99	1
PA233	97.50	139.28	13.214	1.759E+01	10.72	17	3	1.43	2
TE125	110.29	157.56	4.3500	5.702E+00	22.68	6	1	1.50	3
PA233									
CE144	132.71	189.59	6.4250	8.273E+00	15.16	6	1	1.86	4
CE141	144.87	206.96	4.1850	5.347E+00	20.06	5	1	1.30	5
PA233	299.80	428.28	4.8050	5.824E+00	18.29	6	1	1.57	6
PA233	311.54	445.05	27.225	3.292E+01	4.70	9	1	1.92	7
PA233	340.20	486.00	6.0600	7.288E+00	17.95	8	1	2.23	8
CS134	475.38	679.11	6.0650	7.151E+00	13.93	7	1	1.87	9
CS134	563.26	804.66	27.571	3.220E+01	3.66	20	2	2.01	10
CS134	569.27	813.25	49.418	5.768E+01	2.77	20	2	1.94	11
CS134	604.76	853.94	309.61	3.601E+02	0.65	11	1	2.08	12
CS137	661.60	945.14	101.70	1.177E+02	1.30	16	2	1.82	13
ZR95	724.53	1035.04	3.6700	4.228E+00	11.13	8	1	1.83	14
EUI54									
ZR95	756.92	1081.32	3.4300	3.942E+00	12.00	8	1	2.12	15
EUI54									
NB95	755.99	1094.27	10.760	1.236E+01	5.77	12	1	2.55	16
AG110M									
CS134	796.05	1137.21	214.67	2.461E+02	0.74	21	2	2.14	17
CS134	802.17	1145.95	22.098	2.532E+01	2.58	21	2	2.10	18
???	818.78	1169.69	2.6125	2.990E+00	9.91	7	1	1.77	19
CS134	1039.17	1484.53	1.7100	1.934E+00	12.28	8	1	2.49	20
CS134	1168.40	1669.15	3.0725	3.456E+00	10.48	15	2	2.22	21
???	1333.32	1904.74	4.8250	5.396E+01	21.82	7	1	2.18	22
CS134	1365.73	1951.04	4.4950	5.022E+00	5.11	10	1	2.37	23

2 -17 -1978 1534.28
 HQB-13, POS.# 6, 3/16 X 17 IN. HOLE. S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
PA233	93.53	133.62	7.3320	1.039E+01	20.70	6	1	2.05	1
PA233	97.71	139.59	8.9200	1.256E+01	19.45	7	1	1.72	2
TE125	110.39	157.70	4.8450	6.722E+00	30.89	6	1	1.58	3
PA233									
PA233	311.53	445.04	28.540	3.653E+01	9.62	12	2	2.07	4
PA233	339.98	485.69	8.8200	1.123E+01	22.25	8	1	1.89	5
CS134	475.18	678.83	22.872	2.855E+01	8.23	9	1	2.05	6
CS134	563.10	804.42	99.096	1.225E+02	1.88	19	2	2.21	7
CS134	569.17	813.11	185.72	2.307E+02	1.37	19	2	2.07	8
CS134	604.67	863.81	1109.8	1.366E+03	0.36	13	1	2.14	9
CS137	661.55	945.07	351.65	4.309E+02	0.72	15	2	2.01	10
ZR95	756.79	1081.13	3.7400	4.550E+00	16.79	6	1	1.66	11
EU154									
NB95	765.85	1094.07	13.027	1.584E+01	6.92	9	1	2.10	12
AG110M									
CS134	795.95	1137.08	774.97	9.404E+02	0.41	22	2	2.21	13
CS134	802.10	1145.86	77.023	9.343E+01	1.45	22	2	2.26	14
???	818.78	1169.69	9.8225	1.190E+01	6.84	9	1	2.26	15
CS134	1038.99	1484.27	6.5600	7.880E+00	7.54	8	1	2.21	16
RU106	1048.36	1497.66	6.6600	7.972E+00	6.69	8	1	2.73	17
CS134	1168.32	1669.03	10.930	1.301E+01	4.88	10	1	2.24	18
CS134	1365.74	1951.06	17.997	2.128E+01	2.86	13	1	2.48	19

2 -17 -1978 1538.28
HQB-13 SLEEVE POS.# 7: 3/16 X 17 IN. HOLE, S-TJ-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
PA233	86.07	122.96	4.7575	6.419E+00	22.28	7	1	2.04	1
EUI55									
PA233	93.98	134.26	14.479	1.929E+01	6.71	13	2	2.05	2
PA233	97.71	139.59	23.843	3.153E+01	4.88	13	2	1.90	3
TEI25	110.47	157.82	4.5850	5.981E+00	32.11	10	2	2.23	4
PA233									
CEI41	144.88	206.93	6.1800	7.860E+00	17.06	7	1	1.86	5
PA233	299.78	428.26	9.8175	1.184E+01	9.29	7	1	1.94	6
PA233	311.56	445.08	46.270	5.570E+01	2.69	9	1	1.87	7
PA233	340.32	485.17	5.1100	7.315E+00	16.13	8	1	1.46	8
CS134	475.09	678.70	4.7150	5.534E+00	13.94	6	1	1.50	9
CS134	563.30	804.72	19.734	2.294E+01	4.20	18	2	2.24	10
CS134	569.28	813.26	37.170	4.318E+01	2.98	18	2	2.04	11
CS134	604.78	863.97	211.98	2.454E+02	0.81	12	1	2.34	12
CS137	661.73	945.34	67.875	7.821E+01	1.52	10	1	2.12	13
ZR95	724.47	1034.96	5.0450	5.785E+00	8.79	10	1	2.22	14
EUI54									
ZR95	756.82	1081.18	6.9225	7.920E+00	6.27	9	1	2.41	15
EUI54									
NB95	765.97	1094.24	18.775	2.146E+01	3.25	11	1	2.20	16
AG110M									
CS134	796.06	1137.23	147.51	1.683E+02	0.90	20	2	2.24	17
CS134	802.19	1145.99	14.176	1.617E+01	3.26	20	2	2.17	18
???	818.45	1169.22	1.4325	1.632E+00	20.90	11	2	1.60	19
AG110M	884.95	1264.21	91500	1.038E+00	20.45	6	1	2.23	20
CS134	1039.15	1484.50	1.1800	1.328E+00	12.87	6	1	1.91	21
CS134	1168.48	1669.26	1.5900	1.780E+00	11.58	8	1	2.48	22
???	1333.86	1905.51	40250	4.481E-01	27.45	7	1	1.30	23
CS134	1365.80	1951.14	3.2375	3.600E+00	6.15	11	1	2.37	24
AG110M	1384.81	1978.29	23750	2.639E-01	31.91	7	1	2.24	25

2 -17 -1978 1542.10
 HRB-13 SLEEVE POS. # 8; 3/16 X 17 IN. HOLE. S-TO-COLL. = 2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BV	HU	FWHM (KEV)	PK #
???	74.36	106.23	6.6825	9.481E+00	17.19	5	1	1.39	1
CE144	79.36	113.38	9.1425	1.281E+01	16.75	7	1	1.81	2
PA233	85.57	122.24	23.383	3.239E+01	6.06	34	5	1.43	3
EUI55									
PA233	88.18	125.97	31.427	4.334E+01	4.73	34	5	1.98	4
EUI55									
PA233	93.65	134.07	73.158	1.000E+02	2.83	34	5	1.98	5
PA233	97.64	139.48	108.28	1.471E+02	2.41	34	5	1.91	6
TE125	110.28	157.55	36.903	4.940E+01	4.89	14	2	2.31	7
PA233									
PA233	113.92	162.74	13.822	1.844E+01	9.20	14	2	1.96	8
EUI54	122.29	174.69	15.280	2.074E+01	10.80	8	1	1.65	9
CE144	132.85	189.78	159.94	2.103E+02	1.43	10	1	1.85	10
CE141	144.80	206.86	46.555	6.074E+01	4.30	10	1	1.92	11
???	162.10	231.57	4.9275	6.369E+00	21.57	5	1	1.41	12
PA233	299.72	428.17	30.902	3.825E+01	6.97	13	2	1.85	13
PA233	311.50	445.00	200.97	2.482E+02	1.11	11	1	1.96	14
???	328.42	469.18	10.990	1.352E+01	12.22	8	1	2.05	15
PA233	340.09	485.84	22.495	2.763E+01	7.22	10	1	1.85	16
PA233	415.45	593.50	6.6750	8.100E+00	15.83	6	1	1.87	17
CS134	475.13	678.75	5.9700	7.189E+00	17.62	7	1	1.72	18
???	486.80	695.43	17.607	2.117E+01	7.09	9	1	2.12	19
RUI03	496.81	709.74	11.335	1.361E+01	10.90	9	1	2.22	20
???	537.17	767.39	5.4900	6.565E+00	20.41	8	1	1.66	21
CS134	563.12	804.46	28.500	3.399E+01	4.26	8	1	2.19	22
CS134	569.24	813.20	52.565	6.265E+01	2.87	10	1	2.12	23
CS134	604.72	863.09	322.41	3.830E+02	0.69	11	1	2.07	24
???	646.32	923.31	7.7400	9.162E+00	10.07	8	1	2.39	25
AG110M	657.95	939.93	3.9416	4.661E+00	12.95	15	2	2.28	26
CS137	661.67	945.24	113.65	1.343E+02	1.22	15	2	2.13	27
CE144	696.54	995.05	6.5100	7.675E+00	9.61	8	1	2.32	28
ZR95	724.10	1034.42	34.135	4.016E+01	2.59	10	1	2.44	29
EUI54									
ZR95	756.82	1081.17	28.620	3.359E+01	3.27	11	1	2.13	30
EUI54									
NB95	765.93	1094.18	85.322	1.000E+02	1.39	11	1	2.00	31
AG110M									
CS134	796.01	1137.15	226.40	2.650E+02	0.78	21	2	2.16	32
CS134	802.13	1145.91	23.104	2.703E+01	2.75	21	2	2.28	33
???	811.98	1159.97	8.1535	9.536E+00	6.91	13	2	1.97	34
???	815.91	1165.58	2.8239	3.301E+00	15.19	13	2	1.52	35
AG110M	885.01	1264.29	2.0200	2.352E+00	19.24	7	1	2.47	36
???	1065.54	1522.20	4.9700	5.735E+00	7.32	8	1	2.00	37
???	1079.65	1542.36	4.3300	4.993E+00	9.79	10	1	2.46	38
???	1154.26	1648.94	10.240	1.177E+01	4.35	10	1	2.34	39
CS134	1168.56	1669.37	2.6500	3.044E+00	12.85	8	1	2.67	40
???	1231.25	1758.92	6.3800	7.313E+00	6.51	10	1	2.54	41
???	1242.96	1775.66	4.6800	5.362E+00	8.85	12	1	2.61	42
EUI54	1275.30	1821.85	0.88750	1.015E+00	37.77	7	1	1.04	43
CS134	1365.97	1951.38	5.8150	6.634E+00	6.34	10	1	2.69	44

2 -17 -1978 1546.02
 HRB-13 SLEEVE POS.# 9; 3/16 X 17 IN. HOLE, S-TO-COLL.= 2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CE144	79.29	113.27	8.7825	1.232E+01	17.02	7	1	1.68	1
PA233	86.11	123.01	18.612	2.579E+01	6.79	26	4	3.35	2
EUI55									
PA233	88.15	125.93	26.291	3.630E+01	5.36	26	4	1.69	3
EUI55									
PA233	93.84	134.05	45.599	6.240E+01	3.46	26	4	2.04	4
PA233	97.64	139.49	68.941	9.380E+01	2.80	26	4	1.94	5
TEI25	110.29	157.56	25.953	3.478E+01	5.91	12	2	2.23	6
PA233									
PA233	113.96	162.79	9.5167	1.271E+01	12.67	12	2	2.32	7
EUI54	122.34	174.77	7.7750	1.031E+01	19.14	7	1	1.90	8
CE144	132.91	189.88	119.44	1.572E+02	2.21	13	2	2.06	9
CE141	144.82	206.89	29.355	3.795E+01	6.25	9	1	1.75	10
PA233	299.58	427.97	21.817	2.704E+01	7.42	9	1	1.87	11
PA233	311.52	445.33	124.65	1.541E+02	1.71	11	1	1.91	12
???	328.38	469.12	12.347	1.275E+01	14.72	9	1	1.98	13
PA233	340.09	485.84	16.080	1.977E+01	8.82	8	1	1.88	14
CS134	475.22	678.88	8.8675	1.069E+01	12.15	7	1	2.12	15
???	486.84	695.49	14.460	1.740E+01	8.21	8	1	1.97	16
RUI03	497.01	710.02	6.3100	7.587E+00	14.20	6	1	1.98	17
???	537.24	767.48	5.1700	6.189E+00	17.48	6	1	1.84	18
CS134	563.15	804.50	37.100	4.429E+01	3.36	19	2	2.00	19
CS134	569.21	813.15	68.891	8.221E+01	2.47	19	2	2.36	20
CS134	604.72	863.88	414.97	4.935E+02	0.62	13	1	2.05	21
???	646.42	923.45	7.0425	8.345E+00	10.12	7	1	1.88	22
CS137	661.58	945.11	147.24	1.742E+02	1.18	15	2	1.90	23
CE144	696.64	995.19	4.2900	5.063E+00	14.63	8	1	1.91	24
ZR95	724.10	1034.43	23.325	2.747E+01	3.55	10	1	2.32	25
EUI54									
ZR95	756.84	1081.19	18.075	2.124E+01	4.47	10	1	2.15	26
EUI54									
NB95	765.90	1094.15	55.660	6.536E+01	1.86	11	1	2.14	27
AG110M									
CS134	796.01	1137.15	288.42	3.380E+02	0.60	21	2	2.16	28
CS134	802.14	1145.91	29.343	3.437E+01	2.40	21	2	2.14	29
???	811.96	1159.94	4.9300	5.772E+00	18.90	14	3	2.28	30
EUI54	1004.93	1435.61	1.2125	1.404E+00	32.75	9	1	3.36	31
CS134	1039.04	1484.35	2.0100	2.324E+00	13.85	5	1	1.67	32
RUI06	1048.28	1497.54	1.5800	1.826E+00	16.31	5	1	1.76	33
???	1065.55	1522.22	2.8000	3.234E+00	12.36	8	1	2.18	34
???	1080.04	1542.92	3.8425	4.436E+00	12.34	13	2	2.48	35
???	1154.32	1649.03	6.8975	7.938E+00	6.48	11	1	2.60	36
CS134	1168.48	1669.26	3.8100	4.382E+00	9.73	9	1	2.46	37
???	1231.32	1759.03	4.9900	5.726E+00	8.69	13	2	2.63	38
???	1242.99	1775.71	3.7550	4.307E+00	9.12	10	1	2.68	39
CS134	1366.00	1951.43	7.2750	8.309E+00	5.24	10	1	2.63	40
???	1432.45	2046.36	0.31500	3.590E-01	4.50	7	1	1.01	41

2 -17 -1978 1549.58
 HRB-13 SLEEVE POS.# 12; 3/16 X 17 IN. HOLE. S-TO-COLL.=2 IN.

F.O.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	P.K #
CE144	79.36	113.37	10.860	1.510E+01	14.08	8	1	1.78	1
PA233	86.10	123.01	13.105	1.799E+01	8.62	24	4	2.44	2
EUI55									
PA233	88.22	126.03	21.246	2.906E+01	5.81	24	4	1.69	3
EUI55									
PA233	93.88	134.11	22.459	3.045E+01	5.54	24	4	2.12	4
PA233	97.67	139.53	33.618	4.532E+01	4.41	24	4	1.93	5
TEI25	110.48	157.83	20.990	2.786E+01	15.86	20	4	2.36	6
PA233									
EUI54	122.39	174.85	9.3600	1.230E+01	17.78	9	2	1.95	7
CE144	132.86	189.80	136.28	1.777E+02	1.56	10	1	1.86	8
CE141	144.82	206.88	22.495	2.911E+01	7.27	9	1	1.87	9
PA233	299.79	428.27	11.342	1.392E+01	10.26	7	1	1.65	10
PA233	311.54	445.05	66.520	8.148E+01	2.55	10	1	1.87	11
???	328.39	469.13	4.4350	5.415E+00	22.52	6	1	1.31	12
PA233	340.14	485.91	8.6875	1.058E+01	13.09	7	1	1.83	13
CS134	475.14	678.76	6.5075	7.772E+00	15.05	7	1	2.15	14
???	487.04	695.78	8.0225	9.568E+00	14.11	9	1	2.17	15
CS134	563.23	804.62	32.400	3.833E+01	3.50	19	2	2.10	16
CS134	569.26	813.23	59.104	6.988E+01	2.55	19	2	2.05	17
CS134	604.74	863.92	343.01	4.042E+02	0.65	11	1	2.04	18
???	646.26	923.22	5.1300	6.023E+00	14.13	8	1	2.21	19
AG110M	657.39	939.13	3.8329	4.496E+00	12.85	15	2	1.58	20
CS137	661.68	945.26	118.78	1.392E+02	1.16	15	2	2.12	21
CE144	696.84	995.49	4.8600	5.683E+00	12.96	9	1	2.44	22
ZR95	723.93	1034.18	13.607	1.588E+01	5.52	11	1	2.35	23
EUI54									
ZR95	756.94	1081.34	9.7500	1.135E+01	6.02	8	1	2.11	24
EUI54									
NB95	765.94	1094.20	31.045	3.612E+01	2.70	11	1	2.22	25
AG110M									
CS134	796.02	1137.18	241.79	2.807E+02	0.73	19	2	2.15	26
CS134	802.14	1145.92	23.927	2.777E+01	2.66	19	2	1.98	27
???	811.99	1159.98	5.7400	6.658E+00	9.50	9	1	2.32	28
???	818.66	1169.52	1.8700	2.168E+00	24.79	8	1	1.69	29
???	866.89	1238.42	0.99750	1.153E+00	27.95	5	1	1.26	30
AG110M	884.95	1264.21	2.2425	2.590E+00	17.95	9	1	2.41	31
AG110M	937.29	1338.99	0.67500	7.774E-01	41.28	6	1	1.50	32
???	944.72	1349.61	1.0075	1.159E+00	31.09	7	1	2.30	33
CS134	1038.92	1484.17	2.4300	2.784E+00	12.20	7	1	1.98	34
???	1047.98	1497.12	1.0800	1.237E+00	24.64	6	1	1.71	35
???	1065.72	1522.46	2.9925	3.425E+00	11.43	9	1	1.90	36
???	1154.32	1649.02	6.5675	7.489E+00	6.08	11	1	2.31	37
CS134	1168.59	1669.41	3.4850	3.971E+00	9.49	9	1	2.41	38
???	1231.21	1758.87	4.1400	4.707E+00	6.98	8	1	2.25	39
???	1243.11	1775.87	3.2700	3.716E+00	9.02	10	1	2.09	40
???	1333.55	1905.08	0.64250	7.279E-01	25.29	5	1	0.96	41
CS134	1365.99	1951.41	6.2700	7.096E+00	5.91	12	1	2.83	42

2 -17 -1978 1555.16
HR9-13 SLEEVE POS. # 12; 3/16 X 17 IN. HOLE. S-TO-COLL.=2 IN.

F.O.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	475.29	678.99	5.4823	5.426E+20	15.37	8	1	2.19	1
CS134	563.31	884.72	23.149	2.588E+21	3.71	18	2	2.37	2
CS134	569.38	813.29	40.845	4.741E+21	2.75	18	2	2.37	3
CS134	604.78	863.97	243.23	2.779E+22	0.75	12	1	2.32	4
AG110M	558.01	940.31	3.4890	4.218E+20	13.45	15	2	2.58	5
CS137	661.73	945.33	81.233	9.352E+21	1.32	15	2	2.12	6
CS134	796.09	1137.27	165.43	1.686E+22	3.84	23	2	2.17	7
CS134	932.23	1146.05	16.765	1.910E+21	2.96	20	2	2.25	8
???	918.86	1169.79	2.6450	3.211E+20	13.33	9	1	2.44	9
AG110M	884.91	1264.16	1.7575	1.993E+20	12.23	7	1	2.23	10
CS134	1039.31	1484.73	1.5275	1.718E+20	14.34	11	1	2.57	11
RUI06	1045.30	1497.57	1.6130	1.810E+20	12.16	8	1	2.25	12
CS134	1168.48	1669.25	2.2853	2.556E+20	13.28	13	1	2.33	13
???	1236.33	1766.18	.25330	2.790E+21	36.88	6	1	1.36	14
???	1333.41	1904.88	.63530	7.263E+21	20.33	11	2	2.31	15
CS134	1355.97	1951.38	3.7733	4.189E+20	5.77	12	1	2.43	16
AG110M	1385.16	1978.80	.25330	2.887E+21	28.76	8	1	2.72	17

2 -17 -1978 1552.41
HR9-13 SLEEVE POS. # 11; 3/16 X 17 IN. HOLE. S-TO-COLL.=2 IN.

F.O.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
PA233	340.12	485.89	1.9250	2.301E+20	34.87	5	1	2.98	1
CS134	475.27	676.95	4.2900	4.794E+20	15.13	6	1	1.45	2
CS134	563.34	804.77	22.386	2.599E+21	3.81	18	2	2.32	3
CS134	569.29	813.27	39.383	4.535E+21	2.83	18	2	2.37	4
CS134	604.73	863.98	228.31	2.640E+22	3.77	12	1	2.07	5
AG110M	658.10	940.14	4.2924	4.941E+20	8.71	16	2	1.57	6
CS137	661.73	945.32	78.387	8.987E+21	1.37	16	2	2.11	7
NB95	764.47	1092.10	.75530	8.623E+21	33.01	5	1	2.97	8
AG110M									
CS134	796.08	1137.26	158.22	1.803E+22	3.86	23	2	2.17	9
CS134	802.20	1146.00	15.521	1.768E+21	3.13	23	2	2.13	10
???	818.77	1169.67	2.3733	2.697E+20	13.36	7	1	2.13	11
AG110M	884.90	1264.15	2.1730	2.459E+20	13.32	11	1	2.45	12
AG110M	937.58	1339.40	.72750	8.223E+21	21.49	5	1	1.35	13
CS134	1039.24	1484.63	1.2500	1.405E+20	13.18	5	1	1.85	14
RUI06	1048.51	1497.87	1.3975	1.571E+20	13.42	9	1	2.91	15
???	1115.24	1593.23	.23000	2.578E+21	38.71	5	1	1.05	16
CS134	1168.56	1669.38	2.0325	2.273E+20	13.54	9	1	2.47	17
???	1236.54	1766.49	.23030	2.566E+21	39.61	6	1	1.33	18
???	1332.69	1903.85	.55030	6.115E+21	19.50	8	1	1.37	19
CS134	1366.00	1951.43	3.7775	4.195E+20	5.35	11	1	2.85	20
AG110M	1384.15	1977.36	.26042	2.890E+21	22.56	8	2	1.34	21
AG110M	1385.91	1979.87	.23958	2.659E+21	23.69	8	2	1.23	22

2 -17 -1978 1633.27

HRB-13 SLEEVE POS.# 14; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	475.28	578.97	4.8825	5.736E+00	16.34	7	1	1.73	1
CS134	563.32	804.74	24.535	2.855E+01	3.73	19	2	1.91	2
CS134	569.29	813.27	44.819	5.212E+01	2.74	19	2	2.02	3
CS134	604.79	863.99	265.39	3.376E+02	3.72	12	1	2.35	4
AG110M	657.59	939.55	3.4783	4.013E+00	10.92	18	2	1.90	5
CS137	661.72	945.31	86.396	9.965E+01	1.35	18	2	2.18	6
CS134	796.07	1137.24	183.27	2.393E+02	0.82	21	2	2.18	7
CS134	802.20	1146.00	18.887	2.156E+01	2.82	21	2	2.19	8
???	818.91	1169.28	3.7200	4.242E+00	7.54	8	1	2.45	9
AG110M	884.96	1264.23	1.9930	2.260E+00	11.56	8	1	2.22	10
CS134	1039.16	1484.52	2.1300	2.400E+00	9.93	8	1	2.61	11
R1106	1048.63	1498.05	1.5450	1.740E+00	11.89	7	1	2.08	12
???	1153.88	1648.40	.40250	4.514E-01	33.32	7	1	1.97	13
CS134	1168.64	1669.48	2.5100	2.813E+00	9.29	9	1	2.40	14
???	1333.27	1904.67	.65000	7.243E-01	15.91	8	1	2.00	15
CS134	1365.74	1951.06	4.7350	5.270E+00	4.82	14	2	2.13	16
AG110M	1385.04	1978.62	.38000	4.227E-01	21.58	9	1	1.87	17

2 -17 -1978 1557.47

HRB-13 SLEEVE POS.# 13; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
SB125	175.65	250.93	2.0225	2.533E+00	37.37	5	1	1.79	1
CS134	475.19	678.84	4.2500	4.993E+00	20.29	8	1	1.75	2
CS134	563.28	804.69	23.322	2.710E+01	3.82	18	2	1.98	3
CS134	569.30	813.28	42.342	4.886E+01	2.81	18	2	2.34	4
CS134	604.79	863.98	265.81	3.379E+02	0.78	17	2	2.06	5
CS137	661.74	945.34	81.917	9.443E+01	1.43	11	1	2.10	6
CS134	796.08	1137.26	178.33	2.035E+02	0.83	24	3	2.19	7
CS134	802.18	1145.97	18.535	2.166E+01	2.80	24	3	2.28	8
???	819.00	1170.00	2.6375	3.006E+00	13.81	13	2	3.32	9
AG110M	885.18	1264.55	1.3725	1.558E+00	16.42	7	1	1.80	10
CS134	1038.95	1484.21	1.7400	1.960E+00	12.93	10	1	2.04	11
R1106	1048.53	1497.90	1.9450	2.190E+00	10.46	9	1	1.91	12
CS134	1168.65	1669.51	2.4850	2.784E+00	9.63	10	1	2.35	13
???	1333.07	1904.38	.55000	6.125E-01	20.30	8	1	1.80	14
CS134	1365.84	1951.19	4.2225	4.697E+00	5.16	11	1	2.31	15
AG110M	1385.24	1978.92	.35500	3.947E-01	22.60	7	1	2.14	16

2 -21 -1973 831.54
HQB-13 SLEEVE POS.-# 16; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	475.38	679.88	3.5858	4.192E+00	26.12	18	2	1.98	1
CS134	563.31	804.73	17.728	2.352E+01	4.47	19	2	2.05	2
CS134	569.33	813.32	35.288	4.983E+01	3.11	19	2	2.15	3
CS134	604.88	864.88	202.35	2.334E+02	0.84	13	2	2.01	4
AG110M	657.95	939.93	2.7352	3.186E+00	12.68	16	2	2.08	5
CS137	661.75	945.35	67.474	7.746E+01	1.48	16	2	2.19	6
ZR95	723.78	1033.85	.73588	8.055E-01	38.45	7	1	2.03	7
EU154									
CS134	796.88	1137.26	140.93	1.632E+02	0.92	22	2	2.19	8
CS134	802.26	1146.89	15.023	1.787E+01	3.14	20	2	2.01	9
???	818.51	1169.31	1.8328	2.043E+00	11.86	8	1	2.72	10
CS134	1038.92	1484.17	1.4758	1.654E+00	13.49	9	1	2.35	11
RJ106	1048.44	1497.77	1.1408	1.278E+00	14.73	8	1	2.16	12
CS134	1168.65	1669.49	1.7925	2.008E+00	11.64	9	1	2.34	13
???	1333.20	1904.57	1.0353	1.148E+00	12.40	10	1	2.43	14
CS134	1365.87	1951.25	3.2975	3.653E+00	6.08	11	1	2.61	15
AG110M	1384.73	1978.18	.33388	3.322E-01	27.08	8	1	1.38	16

2 -21 -1978 828.58
HQB-13 SLEEVE POS.-# 15; 3/16 X 17 IN. HOLE, S-TO-COL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	563.28	804.68	16.399	1.899E+01	4.78	19	2	2.02	1
CS134	569.31	813.31	31.798	3.679E+01	3.43	19	2	2.06	2
CS134	604.79	863.99	193.58	2.233E+02	0.90	15	1	2.02	3
AG110M	658.88	940.88	4.0472	4.647E+00	8.63	16	2	2.57	4
CS137	661.74	945.35	64.933	7.454E+01	1.51	16	2	2.17	5
CS134	796.89	1137.28	135.69	1.542E+02	0.93	20	2	2.18	6
CS134	802.23	1146.84	14.848	1.596E+01	3.25	20	2	2.07	7
???	818.79	1169.78	1.9888	2.247E+00	11.80	8	1	1.99	8
AG110M	885.88	1264.29	1.6188	1.828E+00	13.81	6	1	1.58	9
AG110M	937.68	1339.54	.80588	9.076E-01	19.83	5	1	1.68	10
RJ106	1048.52	1497.89	1.1758	1.317E+00	16.01	10	1	2.42	11
CS134	1168.52	1669.31	2.0961	2.338E+00	9.89	16	2	1.99	12
???	1173.78	1676.71	.73386	8.185E-01	18.27	16	2	2.12	13
???	1242.91	1775.58	.20588	2.288E-01	38.33	6	1	1.37	14
???	1332.38	1903.29	1.0458	1.159E+00	11.33	15	3	1.34	15
CS134	1365.82	1951.17	3.1538	3.498E+00	6.23	12	1	2.14	16

2 -21 -1978 838.50
 HRB-13 SLEEVE POS. # 18; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	475.27	678.96	3.7450	4.367E+00	15.17	6	1	1.86	1
CS134	563.21	804.59	17.061	1.970E+01	4.44	19	2	1.88	2
CS134	569.31	813.30	29.863	3.355E+01	3.33	19	2	2.13	3
CS134	604.80	863.99	172.43	1.983E+02	0.88	11	1	2.04	4
AG110M	657.96	939.94	3.0656	3.511E+00	10.58	14	2	2.16	5
CS137	661.81	945.44	51.379	5.848E+01	1.63	14	2	2.31	6
CS134	796.08	1137.25	118.81	1.347E+02	1.01	20	2	2.20	7
CS134	802.21	1146.02	12.639	1.432E+01	3.44	20	2	2.14	8
???	818.41	1169.15	1.2000	1.358E+00	27.86	15	2	1.43	9
AG110M	885.02	1264.32	1.4600	1.646E+00	14.75	8	1	2.30	10
CS134	1039.37	1484.82	.91000	1.018E+00	15.79	7	1	2.29	11
CS134	1168.27	1668.96	1.4800	1.646E+00	14.54	10	1	2.70	12
???	1230.76	1758.23	.21500	2.386E-01	38.81	7	1	1.55	13
CS134	1365.99	1951.41	2.8175	3.113E+00	6.10	13	1	2.91	14
AG110M	1384.70	1978.14	.37500	4.141E-01	24.04	10	1	1.04	15

2 -21 -1978 834.48
 HRB-13 SLEEVE POS. # 17; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	475.44	679.20	1.6675	1.943E+00	36.59	7	1	1.57	1
CS134	563.32	804.75	15.341	1.771E+01	4.70	19	2	2.05	2
CS134	569.30	813.29	26.628	3.072E+01	3.55	19	2	2.04	3
CS134	604.79	863.99	157.73	1.813E+02	0.94	12	1	2.07	4
CS137	661.77	945.38	48.140	5.509E+01	1.85	10	1	2.10	5
CS134	796.09	1137.27	111.48	1.263E+02	1.04	20	2	2.12	6
CS134	802.23	1146.05	11.125	1.260E+01	3.62	20	2	2.21	7
???	865.97	1237.10	.26750	3.018E-01	42.76	5	1	0.74	8
AG110M	885.10	1264.43	1.1125	1.253E+00	14.66	5	1	1.87	9
CS134	1039.44	1484.92	.90000	1.006E+00	22.61	12	2	3.49	10
???	1154.52	1649.32	.33500	3.727E-01	30.55	6	1	1.49	11
CS134	1168.34	1669.05	1.4050	1.562E+00	17.49	15	2	2.12	12
???	1333.33	1904.76	.81000	8.955E-01	14.34	8	1	2.07	13
CS134	1366.06	1951.52	2.7825	3.073E+00	6.53	11	1	2.72	14
AG110M	1385.43	1979.19	.32500	3.587E-01	24.11	7	2	1.38	15

2 -21 -1978 844.59
 HRB-13 SLEEVE POS. # 20; 3/16 X 17 IN. HOLE, S-TO-COLL.= 2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	563.37	804.81	5.2316	5.990E+00	7.93	17	2	2.08	1
CS134	569.33	813.33	10.000	1.144E+01	5.50	17	2	2.12	2
CS134	604.82	864.03	57.325	6.538E+01	1.52	11	1	2.04	3
SB125									
CS137	661.84	945.49	16.378	1.858E+01	3.51	12	1	2.26	4
CS134	796.10	1137.28	39.269	4.414E+01	1.75	19	2	2.22	5
CS134	802.28	1146.12	3.9204	4.405E+00	6.21	19	2	2.19	6
AG110M	884.93	1264.19	.92000	1.028E+00	21.19	12	2	3.02	7
CS134	1168.62	1669.46	.64203	7.082E-01	17.35	16	3	2.66	8
???	1173.41	1676.29	.85797	9.463E-01	13.20	16	3	1.31	9
???	1332.94	1904.20	.72500	7.950E-01	13.71	10	1	2.81	10
CS134	1366.36	1951.94	1.0200	1.117E+00	10.47	12	2	2.55	11

2 -21 -1978 841.55
 HRB-13 SLEEVE POS. # 19; 3/16 X 17 IN. HOLE, S-TO-COLL.=2 IN.

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS134	563.30	804.72	9.4400	1.085E+01	6.55	8	1	2.37	1
CS134	569.33	813.33	17.850	2.051E+01	4.38	10	1	2.02	2
CS134	604.80	864.01	110.80	1.268E+02	1.12	12	1	2.07	3
SB125									
CS137	661.61	945.16	35.787	4.078E+01	2.10	13	2	1.77	4
CS134	796.18	1137.40	77.996	8.802E+01	1.23	21	2	2.31	5
CS134	802.26	1146.08	8.3507	9.420E+00	4.22	21	2	2.29	6
AG110M	885.07	1264.38	.87250	9.794E-01	20.31	9	1	2.08	7
CS134	1039.28	1484.69	.58750	6.543E-01	23.03	9	1	2.31	8
???	1048.31	1497.59	.40500	4.508E-01	25.21	6	1	1.69	9
CS134	1168.67	1669.53	1.0100	1.118E+00	14.72	8	1	1.93	10
???	1173.77	1676.81	.58500	6.478E-01	19.18	7	1	2.22	11
???	1333.52	1905.02	.61500	6.771E-01	15.39	5	1	1.28	12
CS134	1365.67	1950.95	1.2827	1.410E+00	9.08	15	4	1.42	13
CS134	1366.95	1952.78	.73978	8.136E-01	11.91	15	4	5.57	14
AG110M	1384.37	1977.67	.21250	2.335E-01	24.02	7	1	1.68	15

2 -17 -1978 1257.59
 HRB-13, BACKGROUND CHECK, .010X1X17 IN. PB SLIT

F.P.	ENERGY (KEV)	PEAK CHNL	CPS	GAMMA/SEC	ERR (%)	BW	MU	FWHM (KEV)	PK #
CS137	661.70	945.28	.71000	8.673E-01	16.65	9	1	2.11	1
???	835.09	1192.99	.88729	1.013E+00	10.57	7	1	2.17	2
???	1173.80	1676.86	26.331	2.959E+01	0.48	13	1	2.32	3
???	1292.20	1846.00	.68444	7.658E-01	7.52	9	1	2.48	4
???	1333.12	1904.46	47.328	5.288E+01	0.28	16	1	2.55	5

Appendix B

ADDITIONAL DETAILS ON DECONSOLIDATION OF FUEL RODS

As part of the standard procedure for fuel rod deconsolidation (Procedure MET-ER-TS-44), the electrolyte solution is analyzed for uranium and thorium content. The results for the selected deconsolidated rods are shown in Table B.1. After irradiation, the particles would contain approximately 11.1×10^{-5} g U for the Amberlite resin kernels and 1.4×10^{-5} g U for the Duolite resin kernels. The solutions contained appreciable amounts of uranium, which is another indication of the high failure fractions experienced by the HRB-13 fissile particles.

Table B.1. Results of uranium and thorium content analysis of HRB-13 deconsolidation solutions

Sample	Solution content, ^a g/L	
	Uranium ^b	Thorium
HRB-13-2	0.0009	<0.001
HRB-13-9	0.0001	<0.001
HRB-13-10	0.0004	<0.001
HRB-13-15	0.0002	<0.001
HRB-13-17	0.0004	<0.001
HRB-13-18	0.0003	<0.001
HRB-13-19	0.0002	<0.001
HRB-13-20	0.0003	<0.001
HRB-13-21	0.0004	<0.001
HRB-13-22	0.0017	<0.001
HRB-13-23	0.0007	<0.001
HRB-13-24	0.0003	<0.001
HRB-13-25	0.0005	<0.001
HRB-13-26	0.0004	<0.001
HRB-13-31	0.0009	<0.001

^aRods are deconsolidated with 0.400 L of nitric acid solution (8 N).

^bBurnup of uranium is taken into account.